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Strategies for Automatic Track Initiation

Edited by

Dr. S. J. Rabinowitz

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STRATEGIES FOR AUTOMATIC

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Edited by

(10) Dr. S.J. Rabinowitz

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TECHNICAL PREFACE

The 36th Technical Meeting of the Avionics Panel of AGARD was held in Monterey, California, USA, 16th and 17th October 1978. The meeting, "Strategies for Automatic Track Initiation" was held in response to the growing awareness in the radar community that automatic tracking is potentially realizable with today's technology.

The concept of an automatic tracking radar is appealing. It holds forth the promise of increasing [illegible] number and accuracy of target tracks while simultaneously reducing the cost of manning the radar. While the promise is great, the problems are formidable. An automatic tracking radar must operate in a variety of environments, including some which would rapidly overload the machine if it were not capable of making intelligent decisions in real time. An automatic tracking radar must adapt to its environment to conserve its resources and to apply them intelligently.

The radar must cope with natural interference such as clutter and multi-path, and with man-made interference due to jammers or chaff. It must track isolated targets and tight clusters of targets flying in formation. It must track maneuvering targets and targets which fly crossing trajectories. If the automatic tracking radar is part of a surveillance network, it should be capable of correlating tracks obtained by more than one radar from a single target and of handing over tracks to other radars in the network as targets fly out of the field of view of one sensor and into the field of view of an adjacent one.

The critical issue for an automatic tracking radar is the extraction of targets from clutter and maintaining tracks on targets which enter regions of heavy clutter. Many of the papers at the meeting dealt with these two issues. Classical techniques based on the use of CFAR and MTI have been superseded thanks to the availability of modern digital techniques. It is now possible to store a complete clutter map for each of the range, angle and doppler cells of a modern 2-D or 3-D radar. The maps are updated each time the radar scans its surveillance volume. The use of a clutter map, in one form or another, provides the basis for target extraction and track initiation for most of the radars described at the meeting. The success of one technique (MTD) is illustrated in Figure 13 of the paper by O'Donnell and Muehe.

The adaptability inherent in an electronically steered phased array also has great implications for the design of multifunction radars which combine volumetric search and multiple target tracking. Van Keuk's paper describes an experimental system (ELRA). Not only can phased array radars adapt their search and track rates to respond to the environment, they can adapt their antenna patterns as well. The state-of-the-art of adaptive antenna nulling is still in its infancy and none of the papers at this meeting reported on the role of adaptive arrays in automatic tracking radars. We will surely hear more about this subject in the future

The research reported at this meeting and the promise of new developments yet to come clearly show that the radar art, although mature, has lost none of its youthful vigor.

S.J.RABINOWITZ

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AN AUTOMATIC TRACKING SYSTEM BASED ON THE STATIONARY PLOT FILTER

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SUMMARY

This paper is concerned with the design of an automatic tracking system applicable to shipborne non-MTI radars. It is based on the stationary plot filter (SPF), which cancels stationary and slow moving detections and also provides data for both control of the first threshold and adaption of the track confirmation rules. The design of the system is discussed, with the emphasis on the SPF. Some experimental results are presented, which show how the performance of the filter is affected by the values of its parameters and also compare the performance of the SPF based approach with that of the more conventional Moving Target Indication (MTI).

1. INTRODUCTION

1.1. The aim of automatic track extraction systems is to provide rapid and reliable formation of tracks on new targets, together with the updating of all tracks in an accurate and reliable manner. It becomes increasingly necessary to automate this process as the speed of the threats increases and, as a consequence, the required reaction times are reduced. Few problems are encountered in non-cluttered areas, but difficulties in the form of excessive numbers of false tracks arise in the face of clutter and interference. The function of a track extraction system is to automatically extract information from the radar video on all the moving tracks in the radar cover, in realistic operating conditions which include clutter and interference, while maintaining a low rate of generation of false tracks.

1.2. One of the major difficulties in the design of automatic track initiation systems is the presence of clutter in the environment and some means of combatting its effect is therefore essential for effective operation. Moving target indication (MTI) systems are an obvious solution to this problem, but some operating conditions, such as pulse-to-pulse frequency agility, may preclude their use. It is nonetheless highly desirable to maintain an automatic capability under such conditions because clutter tends to produce false tracks, which not only cause overload in the data processing system but can also lead to confusion of the total track picture. Recent advances in technology have revived interest in area MTI systems, which do not necessarily depend on coherent transmissions for their operation, but these cannot easily be used with moving radars, due to difficulties in the corrections required for platform motion with the large number of cells involved. This leads to the consideration of post-plot extraction techniques, where the processing required is more likely to lie within the scope of a general purpose computer.

1.3. It has been estimated that several thousand detections per revolution of the radar can be generated by land clutter, but that the general purpose computer used for the track processing can handle only several hundred. This leads to a requirement to reduce the number of plots fed to the tracking computer by more than an order of magnitude. The stationary plot filter (SPF) accomplishes this by taking advantage of the fact that land clutter returns tend to appear in the same position from scan to scan and removes from the plot extractor output those plots which do not appear to be moving, thereby preventing saturation of the rest of the data processing system.

The problem of automatic operation would be solved by the SPF if all the clutter detections were removed, leaving detections from wanted targets unaffected. Inevitably in a real world this is not the case and the detection density in clutter will still be higher than in the clear, even at the output of the SPF. If the rules for promotion of tentative tracks to confirmed are formulated so that the desired track false alarm rate is achieved in the clear, then too many false tracks will be generated in cluttered areas, even though the number is very much reduced by the action of the SPF. Conversely, if the promotion logic is designed to produce an acceptable number of false tracks in clutter, then the track formation range in the clear will be seriously degraded, particularly for the high speed tracks, which are of greatest interest. The obvious solution to these conflicting requirements is to adapt the track promotion logic as the detection density changes. The SPF files contain the information required to do this and each output plot message includes data on the local detection density, which is used by the adaptive track initiation logic as a basis for varying the promotion rules. In this manner, tracks in the clear may be quickly initiated, while those in cluttered (or otherwise confused) areas are confirmed less quickly, if at all.

The stationary plot filter is designed to deal with land clutter and when faced with clutter which does not correlate from scan to scan, its cancellation efficiency is very much reduced. Each entry in the filter store has associated with it a capture area, which effectively blanks out part of the radar cover as seen by the tracking process. The capture areas around land clutter points are effectively stationary and contribute to the rejection efficiency of the filter; those from non-correlating clutter, however, do not, and, what is worse, remain in the filter store for several scans before being cancelled. This has the effect of blanking out such areas at relatively low clutter densities and therefore suppressing all returns (including targets). The effect of this is to provide a system which, although it has the desired low track false alarm rate, tends to over-densitise the radar output as seen by the data processing system in areas of clutter where detections which do not correlate from scan to scan are produced. As the process depends for its viability on inter-clutter visibility, a better solution might be to control the first threshold so that the maximum density of detections is limited in areas identified by the stationary plot filter as cluttered. This allows the possibility of super clutter visibility in non-correlating clutter and improves the probability of inter-clutter visibility in land clutter.

The stationary plot filter has now evolved from a simple device for the cancellation of clutter returns to the heart of an integrated automatic tracking system, feeding information back for first threshold control and forward for adaption of the track initiation logic.

1.4. System Description

A block diagram of the data processing system is shown in Figure 1. Radar video is fed into the plot extractor, whose function is to identify those groups of returns having the characteristics of targets, while rejecting those from other sources (eg noise, clutter and interference). Plots output from the extractor are passed to the stationary plot filter, which holds data on all tracks which appear to be stationary (ie correlate from scan to scan). Each incoming plot is compared with this data and if the new detection falls within a defined capture area around one of the filter entries, the plot is deemed to be clutter and is cancelled. If, however, there is no correlation, the plot is passed on to the tracking process for comparison with known system tracks. If this results in an association the appropriate track is updated. In the absence of an association, it is concluded that the plot is from a new moving object, a new stationary object, or is otherwise spurious. As a decision as to which is applicable cannot be made at this stage, such plots are used both to initiate new moving tracks and as new entries in the stationary plot filter store. On subsequent scans either the new track or the stationary plot filter entry will become confirmed, the other being cancelled due to lack of supporting data. If the plot is spurious, however, both the filter entry and new track are cancelled. The plot processing logic is summarised in Figure 2. This arrangement introduces the need for feedback from the tracking to the stationary plot filter, but is the simplest method of ensuring that tracks which slow down (eg helicopters) and those which always move slowly (eg ships) are not cancelled by the filter once the autotrack has been established. The stationary plot filter also feeds information on local detection densities back to the first threshold and forward to the automatic track initiation system.

The main constituents of the data processing system are discussed in the following sections of this paper, the emphasis being on the stationary plot filter.

2. PLOT EXTRACTOR

The plot extractor design is fairly conventional, consisting of a cell averaging constant false alarm rate (CFAR) processor, followed by integration of the single level quantised video. Although more sophisticated CFAR processors are available, none of them offer ideal performance and the subsequent processing has therefore to be tolerant of this non-ideal behaviour. As a result, simplicity is opted for. The main elements of the extractor are shown in Figure 3.

As the false alarm rate at the output of the CFAR is, in general, higher than that desired, an additional margin is added at the first threshold to reduce the false alarm rate to the required level, usually on the assumption that the input has a Rayleigh distribution. The false alarm rate at the second threshold is further reduced by integrating the output of the CFAR across the radar beam. A staircase integrator is used, which, like the well-known m-out-of-n detector, is relatively insensitive to target fluctuation and impulsive interference (Marcoz, F and Galati, G, 1972). The combined effect of these 2 processes is to reduce the probability of a false target being generated from noise to approximately 10^{-6}. This figure assumes the unwanted input to be Rayleigh and uncorrelated from pulse-to-pulse. The probability of false alarm is greatly increased when the input does not conform to these assumptions, as is the case for most forms of clutter, and additional processing is included at a later stage to take account of this.

3. TRACKING

The tracking system consists of 3 separate processes, namely plot-to-track association, track updating and track initiation.

3.1. Association and Updating

Plot-to-track association is the process of comparing plots with known tracks and deciding on the correct pairs. When a pairing is made, the track information can be updated to produce refined estimates of position and velocity. The track updating algorithm is required to smooth the incoming data in order to produce reliable estimates of track position, speed and heading. The process is designed to smooth out the measurement errors, while retaining a good response to manoeuvres and consists of a least-squares α, β process. The algorithms used have manoeuvre response and missed observation handling based on Kalman filter theory, with simplifications applicable to surveillance radars in order to reduce the computer load.

At first sight it appears that tracking should be carried out in a polar co-ordinate system, but unfortunately straight tracks are generally non-linear in this representation. It is clear, however, that manoeuvre detection ought to be carried out in polars. One way out of this dilemma is to use a cartesian co-ordinate system aligned along and across the line-of-sight to the target (sensor orientated cartesians). Further details of the tracking system can be found in the references Holmes, J E, 1977 and Quigley, A L C et al, 1976.

3.2. Track Initiation

The requirement of a good auto-initiation process is to achieve an optimum balance between the speed of initiation of new tracks and the rate of generation of false tracks. Since measurement conditions can vary significantly with position and time, the optimum scheme must be adaptive. Without the ability to adapt its parameters the initiation process cannot remain optimum under all conditions.

On successive radar scans the plots which remain after failing to associate with existing tracks can be used to form new tracks. Two such plots from different scans will be used to form a tentative track, which will either be confirmed as genuine or deleted as further plots do or do not associate with it.

The method used is based on probability theory, where the conditional probability of validity for each tentative track is determined from the observed measurement sequence and the observed local detection environment. By using the a priori value for the ratio of valid and invalid track probabilities and the probabilities of successful measurements on such tracks, the a posteriori value for the ratio of valid and invalid track probabilities can be found. The rule used is based on Bayes theorem and is derived from it in a simple manner (Holmes, J E, 1977 and Quigley et al, 1976). The a posteriori value after one scan is used as the a priori value for the next scan and the measurement attempt made on that scan is then used to update the a priori value to give a new a posteriori value.

Prior to track formation or updating attempts occurring in any given area some value for the likely probability of validity of any track formed from target detections within that area can be postulated. Such factors as false target detection rate, true target detection rate, expectancy of target(s) based on data from other sensors or flight plan information, SPF efficiency or rate of leakage of false target detections to the track formation logic can all influence the a priori value of valid track probabilities.

Change of track status to a confirmed level or deletion occur if the probability of validity reaches suitable upper or lower limits based on the acceptable false alarm rate for the track promotion logic or the likely deletion of a true track respectively. The false alarm rates thus set are constant false alarm rates and enable the logic to operate under any condition with known and acceptable performance.

4. STATIONARY PLOT FILTER

4.1. The basic principles of the stationary plot filter are simple. Plots (output from the plot extractor) which are at or near the positions of plots received and stored on previous scans are deemed to be clutter and are therefore cancelled. The stored plots result from echoes from land clutter and slow moving targets. New plots which are not close to any stored plot are output by the filter and are also used to form new entries in the store, provided they do not associate with any existing track.

The position of a stationary plot is stored for a specified number of scans before being wiped, unless a new plot occurs in close proximity, in which case its life in store is extended and its position modified by the position of the new plot (ie a smoothing process takes place). The parameters which control the effective memory length merit consideration in more detail. The memory is controlled by a consistency counter, which is incremented by γ on each scan when the filter entry is updated and decremented by δ (usually one) on each scan where no association is made. When a new filter entry is created, the counter is set to an initial value, usually equal to γ. The maximum value of the counter (M) limits the time an entry which is not being updated can remain in the filter, as entries are cancelled when the counter reaches zero.

Clearly, clutter points with high detection probabilities are likely to have entries in the stationary plot filter and are therefore likely to be cancelled, ie the probability of observing them at the output is low. Equally, clutter points with low detection probabilities are not likely to have filter entries, but, by virtue of their low detection probabilities, are unlikely to be seen at the input and hence also at the output. From the foregoing, it is expected that there will be some value of the detection probability for which there exists a maximum value of probability of presence at the output of the SPF. Figure 4 shows a set of curves which relate the detection probability at the input and output of the filter for various parameter settings. Note that the expected maximum is clearly visible and that it is a function of the memory parameters. It is also clear that the output detection probability can never exceed the input detection probability.

In the case where the input consists solely of detections from land clutter, the longer the memory length, the greater the cancellation efficiency of the process. However, as has already been pointed out, if other forms of clutter (or interference) are considered, the situation is somewhat different, as each entry in the filter has associated with it a capture area, which effectively blanks out part of the radar cover as seen by the tracking process. The SPF relies for its viability on inter clutter visibility and so the number of spurious entries in the filter store needs to be minimised in order to maximise the area where detections of moving tracks can be made. The values of the parameter γ and to some extent the counter maximum (M) require to be a compromise between cancellation of real returns with low values of detection probability and limitation of the time which spurious entries remain in the filter memory.

The other SPF parameter which needs to be considered is the size of the capture area around each filter entry. This area would normally need to be several times the radar measurement standard deviation (to allow for radar measurement errors), but is likely to be less than the radar resolution capability (Quigley, A L C, 1973). The size of the capture area clearly dictates the minimum speed that a target requires to evade capture by the filter and hence allow automatic initiation to occur. The size of the capture area, therefore, requires to be a compromise between filter efficiency and a reasonable escape speed.

Using minimum escape speeds of up to a few hundred km/hr, this system allows automatic initiation on fast tracks where it is most needed, whilst allowing manual initiation on slower moving tracks. This is achieved simply by removing the appropriate filter entry, which ensures that subsequent detections are output to the tracking process.

The filter is required to produce information relating to the local clutter density with each output plot message. As the data structure that produces the most efficient search, and therefore the smallest processing time for the SPF program, will not, in general, have the optimum structure for the plot density requirement, a separate data store is maintained for this purpose. Ideally the local detection density should relate to an area centred around the plot of interest, but this would increase the search time of the process by an unacceptably large amount. A compromise solution is, therefore, to divide the radar cover into a number of cells, each of which should contain sufficient radar resolution cells to give a reasonable plot count under a range of clutter conditions. The optimum dimensions of the cells are still under consideration, but it seems to be reasonable to use approximately equal dimensions in range and cross range. A typical size might be 3 km by 6°, which is square at approximately 32 km. A count is maintained on each scan of the number of detections received in each cell and detections output from the filter are tagged with the count appropriate to the cell in which they fall. This system, is, of course, only accurate for plots near the centre of the cell and is likely to be in error for those near the edges. It may be possible to improve the accuracy by using a weighted average of the density in the surrounding cells.

A similar storage structure is required for feedback to the first threshold in order to implement area sensitivity control. The algorithms used to calculate the required threshold offset could vary from a simple fixed value for those cells deemed to be cluttered to a very much more complex system. It is relatively easy to determine when to raise the threshold, but rather more difficult to decide when to lower it. A simple system can be envisaged which raises the threshold when the number of plots (corrected for those which associate with known tracks) reaches an upper limit, but only lowers it again when the number of plots falls to some lower limit. The threshold cannot be reduced below that set by the normal CFAR system and the plots in those cells in which the threshold is being changed will not be considered for initiation of new tracks or even, in extreme conditions, for updating existing tracks, until the threshold is stable. The maximum allowable number of plots per cell should be set to a level where only a few per cent of the resolution cells are filled, to allow maximum probability of inter-clutter visibility and let through only the larger fixed scatterers, which will be dealt with effectively by the SPF. In this manner it is expected to evolve a system which will approach the performance of an area MTI, but which is more amenable to fitting to shipborne radars.

Aspects of the system design such as the size and number of cells in the clutter files and the optimum algorithms for threshold control are currently under investigation, using both simulated and recorded data. An experimental real-time track extraction system is also being built and will be used for land and sea based trials to validate the design and determine the performance of the system under realistic conditions.

4.2. Data Structure

A section of the computer store is used as a file to store the positions of stationary plots. Each new plot received from the plot extractor needs to be tested for association with stationary plots held in the store. In order to reduce the search time, the data structure needs to be efficiently organised.

Assuming that every new plot from the plot extractor associates with a stored stationary plot and that association tests stop once association is made (so that the average search is through half the stored plots, assuming they are not ordered), then the total number of tests per input plot is approximately equal to half the number of stored plots. It has been found experimentally that the number of stored plots is approximately double the number of input plots per scan. With 1000 input plots, the number of tests required per scan is of the order of a million, which is prohibitively large. This can be considerably reduced by dividing the radar coverage area into a number of segments of equal size in terms of range and bearing. The number of association tests is then reduced and is dependent on the number of stationary plots stored per occupied segment. If each plot is perfectly stationary then, for each input plot, the segment containing its associated stored plot can be immediately found. However, in practice plots are not perfectly stationary and if segment sizes are smaller than the association box size, additional work must be done in searching for an occupied segment before testing for association can take place and additionally several segments will need to be searched for each input plot. Another disadvantage of having a large number of segments is that they all have to be examined once per scan to decrement the confidence counter of any unassociated stationary plots. Time also has to be spent in examining empty segments to see if they are occupied. Thus there is an optimum number of segments for a given clutter scenario.

A factor which influences this optimum number (and therefore the processing time) is the shape of a segment. Using the local ground clutter scenario, the effect of changing the segment shape was investigated (Shepherd, A M 1976). All the 3 shapes used showed a decrease in processing time with the number of segments (n), but the best for a fixed value of n was n segments in bearing (and one in range) followed by n in range (and one in bearing), the worst being with 64 in bearing and the rest ($^n/_{64}$) in range. The most efficient shapes, of n segments in range or bearing, cannot generally be used as the segment size would almost certainly be smaller than the association box and several segments would therefore require to be searched for each input plot. This condition imposes a minimum segment size in both range and bearing. As the plot extractor used transfers data in octant ($\frac{1}{8}$ scan) blocks, it was convenient to use 8 bearing sectors.

The optimum number of segments is now required and in order to obtain this, the number of instructions in the compiled code was found for each procedure and, assuming a mean instruction time of 3 μs for the general-purpose computer used, the processing times were calculated for different values of n (Shepherd, A M 1976). It was assumed that the stored plots in each segment are not ordered and that the search is complete once an association is made. Figure 5 shows a graph of processing time against number of segments for 50% and 100% association, with 1000 input plots/scan. It can be seen that, for these conditions, 4096 is a reasonable number of segments to use, as it is convenient to use a power of 2, and that the computer used would take of the order of one second to process 1000 plots. Figure 6 shows

processing times for 600-2000 input plots per scan as a function of number of segments, assuming 90% association. It can be seen that the processing time is a fairly linear function of the number of input plots when 4096 segments are used.

The system is programmed completely in the high level language CORAL 66 and it is estimated that the processing time could be reduced by up to 20% by using a low level language to code the critical parts of the program, in order to overcome inefficiencies in the CORAL 66 compiler. This would, however, lead to less comprehensible program, which would therefore be more difficult to maintain. Processing time could also be reduced by using a more complex search process and having a list ordered in bearing (or range). This would reduce the average number of tests for association in each segment since the search, beginning with the stationary plot having the lowest bearing in a segment, would proceed through the list only until the maximum bearing for association had been exceeded. On the other hand additional instructions would be required for keeping this list ordered. This method is only likely to be effective with relatively large numbers of plots per occupied segment and the optimum number of segments is therefore likely to be smaller than with a non-ordered system. Processing time for this method has not been calculated but it may be worth considering if faster processing is necessary.

4.3. Experimental Results

4.3.1 Parameter Settings

Experimental measurements have been obtained from land clutter using 3 radars with pulse lengths of 2 μsec and 50 nsec on the same site and of 250 nsec on a different site. The optimum (standard) value for each of the parameters was determined empirically and each was then varied in turn while keeping the others constant. The smoothing factor used to update the positions of stationary plots relates to a fixed value of α in a position only tracking filter. The standard values are tabulated in Figure 7 and the results are summarised in Figures 8-13.

In Figures 8 and 9 the capture areas are shown in terms of radar beamwidths and range bins (plot extractor range increments). It can be seen that the results obtained are generally similar for the 3 radars and that there is an optimum size of capture area of approximately 6 range bins by 1.5 beamwidths. In the case of the 50 nsec pulse length radar this represents a minimum escape speed of 40 km/hr, the corresponding figures for the 250 nsec and 2 μsec radars being 200 and 400 km/hr respectively. Increasing the memory parameters (ie γ and the initial and maximum values of the confidence counter) over the standard values appears to have little effect on either the efficiency of cancellation or the total number of plots held in the store. The value of the smoothing factor (α) also has little effect, the optimum value being about 0.5.

The clutter scenario at the second site was markedly different from that at the first, there being a significant number of detections which were likely to be from motor vehicles moving on the local road system. This is the most likely explanation of the signficantly worse cancellation efficiency and its steady improvement with increasing range capture area obtained with the 250 nsec pulse length radar. Even so, the results demonstrate that the optimum filter parameter settings are relatively insensitive to both the radar pulse length and the observed clutter scenario, although the cancellation efficiency is obviously affected.

It should be emphasised that this data was obtained from land based sites and the process has yet to be validated for shipborne use, where the characteristics of the observed land clutter may well be different due to the motion of the ship and the change in grazing angle.

4.3.2 Filter Performance

Using the 250 nsec pulse length radar recordings were obtained of both non-MTI and MTI plots, the radar being switched to MTI mode after 23 scans. Unfortunately it was not possible to record data from both channels simultaneously. The radar was radiating over a sector from 163° to 318°, with a minimum range of 12 km and a maximum of approximately 60 km.

The track initiation rule used was fixed at 2 plots on consecutive scans for tentative track formation and a further one from the next 2 for confirmation.

It can be seen by comparing the SPF output (Figure 15) with its input (Figure 14) that a significant proportion of the returns from the land clutter area are cancelled by the SPF, while the detections from the moving targets are not seriously affected. Of course, the slower tangential tracks are likely to lose more detections than the radial ones, particularly at the longer ranges. Figures 19 and 20 show that during the first few scans, as the SPF builds up its picture of the clutter environment, the number of output plots is high and the cancellation efficiency is therefore low. After a warmup period of 2 scans, during which automatic initiation is inhibited, the cancellation efficiency fluctuates between 80% and 90%. This has the effect of inhibiting the first 2 scans of detections, including those from moving tracks, which therefore appear 2 scans later in Figure 15 than Figure 14. All 4 of the tracks visible in the non-MTI data are also present in the SPF output. However, only 2 of these are confirmed by the autotracking system (Figure 16). Both the missing tracks are nearly tangential and one fails to run for sufficient scans to be confirmed, while the speed of the other is such that every second detection is absorbed by the SPF, so that the tentative track initiation criterion of 2 outputs on consecutive scans cannot be met.

From Figure 16 it is clear that no false tracks are initiated from the residual land clutter plots not cancelled by the filter and that only a few plots on moving tracks have been lost, which does not seriously degrade the tracking system performance. Unfortunately data which demonstrates the ability of the system to initiate and track targets in cluttered regions is not available, although this has been observed using the real-time radar system.

4.3.3 Comparison with MTI

It can be seen from Figure 19 that the number of plots output from the MTI channel is nearly 2 orders of magnitude less than the non-MTI and one order less than the SPF output. The number of tentative tracks generated from the MTI plots is similarly about one tenth of the number from the SPF output (Figure 21). However, the number of confirmed tracks is the same, the third track only entering the radar cover just after MTI was selected and therefore not being present in the non-MTI data. Of the 4 tracks visible in the non-MTI picture (Figure 14) only 2 appear in the MTI data (Figures 17 and 18). However, as pointed out above, only 2 of the tracks in the SPF output were confirmed by the autotracking system (Figure 16). Although this is the case, the data on the other tracks was available (at the input to the filter), whereas in the case of the MTI it was not. This was demonstrated by using an association gate of half the normal size and the resultant track output is shown in Figure 22, where 3 of the original 4 tracks are visible, the fourth again not being present for sufficient time to be confirmed. However, a further 2 tracks were produced from the area of land clutter and these appear to have sufficient detections to be genuine. It is concluded that they are from road vehicles, as their speed is of the order of 70 km/hr. This clearly demonstrates the fact that while the MTI is blind to all tracks with no radial velocity component, the SPF has a finite, range dependent, minimum speed for detection of tengential tracks. At close range, where land clutter is most likely to be detected, the minimum speed for initiation of tangential tracks may well be less than that for radial. Once a tentative track is formed, of course, the SPF ceases to cancel detections whatever the speed and slow tracks may therefore be manually initiated if necessary.

The performance of an SPF based system in practice may well be superior to that suggested by these results, as adaptive initiation rules allowing 2 out of 3 (or even 4) scans in clear areas would reduce minimum speeds for automatic initiation, particularly for long range tangential tracks. Indeed, it is possible, in clear areas, to have automatic initiation of all tracks, by allowing the SPF to determine in which areas it is unnecessary to suppress detections. The addition of first threshold control should also improve performance in clutter which does not correlate from scan-to-scan and reduce the computer load in that which does.

As the MTI is blind to tangential tracks, it is therefore only useful for detecting tracks with radial velocity components in cluttered areas, where it has sub-clutter visibility. The SPF, on the other hand, can be used for all tracks in the clear, but has no sub-clutter capability and therefore relies on inter or super-clutter visibility, under which conditions both radial and tangential tracks may be visible, depending on their range. It is therefore clear that to obtain the optimum performance under all conditions, both MTI and non-MTI channels should be combined, as their outputs are complementary. This is confirmed by the fact that the MTI and SPF system did not recognise the same 2 tracks out of the 4 that were obviously present.

5. CONCLUSION

The automatic surveillance radar track extraction which has been described is capable of achieving low false track generation rates while operating in realistic radar environments. In order to achieve this goal, several stages of false alarm rate control are incorporated, culminating at track level with the adaptive initiation system. The basis of the system is the stationary plot filter (SPF), which provides data for area sensitivity control at the first threshold and adaptation of the track promotion logic. It is expected that the processing power required for the SPF together with the automatic initiation and tracking functions, will be within the capability of 2, or maybe 3, mini-computers, depending on the parameters of the radar involved. It can be seen that it is not necessarily possible to optimise components of the system in isolation and that it may be more cost-effective to incorporate extra processing to correct known deficiencies than to attempt to overcome them in isolation.

From the foregoing it is clear that, in order to obtain the best performance from future surveillance radars, the data processing should be designed as an integral part of the radar and include complementary MTI and non-MTI channels, so that the performance of the system as a whole may be optimised.

ACKNOWLEDGEMENT

My thanks are due to several colleagues who have contributed to this work and in particular to Mr A M Shepherd for his invaluable assistance with the software aspects.

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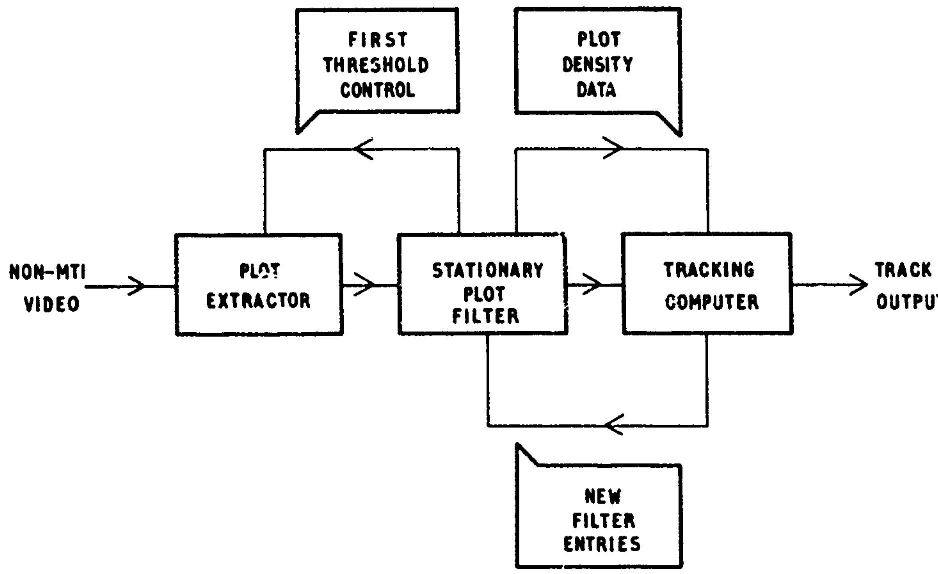

FIGURE 1 OVERALL PROCESSING ARRANGEMENT

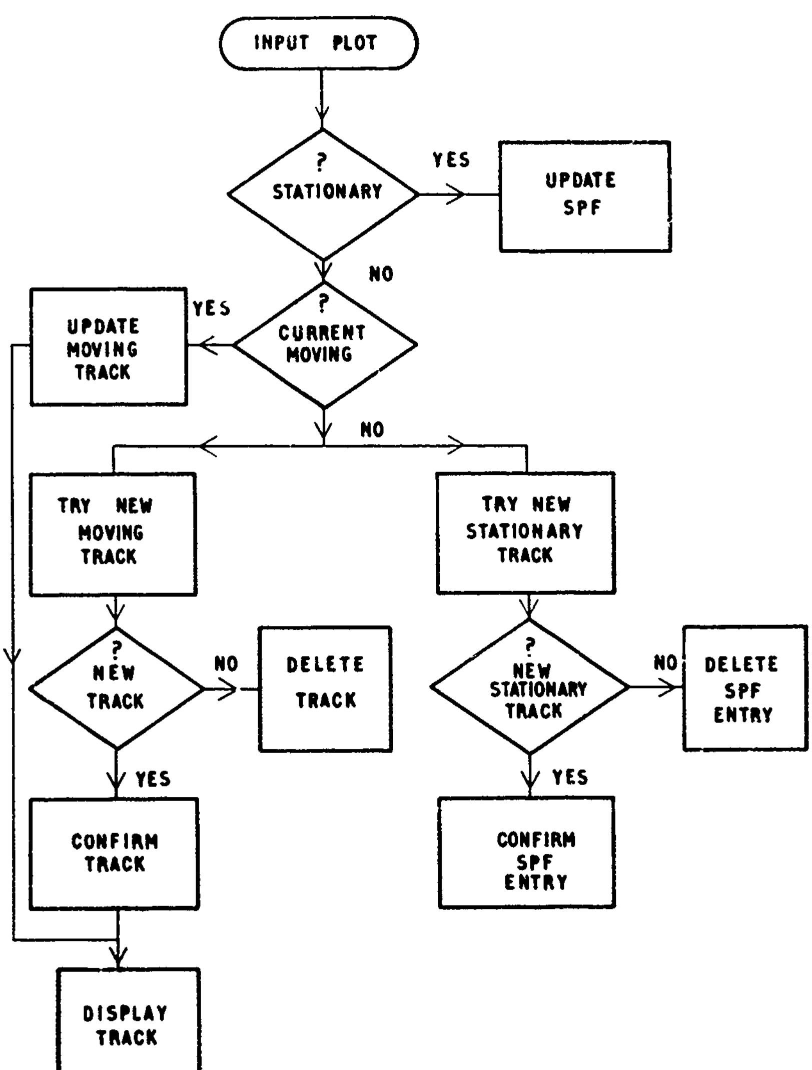

FIGURE 2 PLOT PROCESSING LOGIC

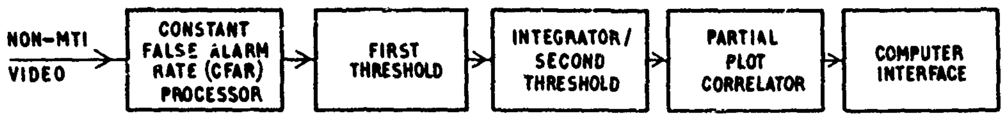

FIGURE3 MAIN ELEMENTS OF PLOT EXTRACTOR

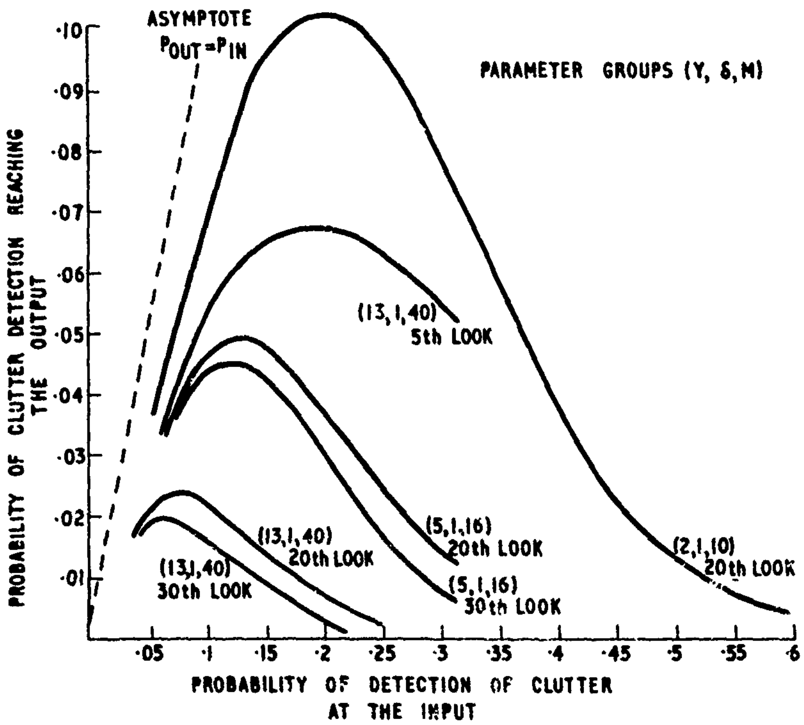

FIGURE 4 PERFORMANCE OF STATIONARY PLOT FILTER AS DETERMINED BY THE VALUES OF ITS PARAMETERS

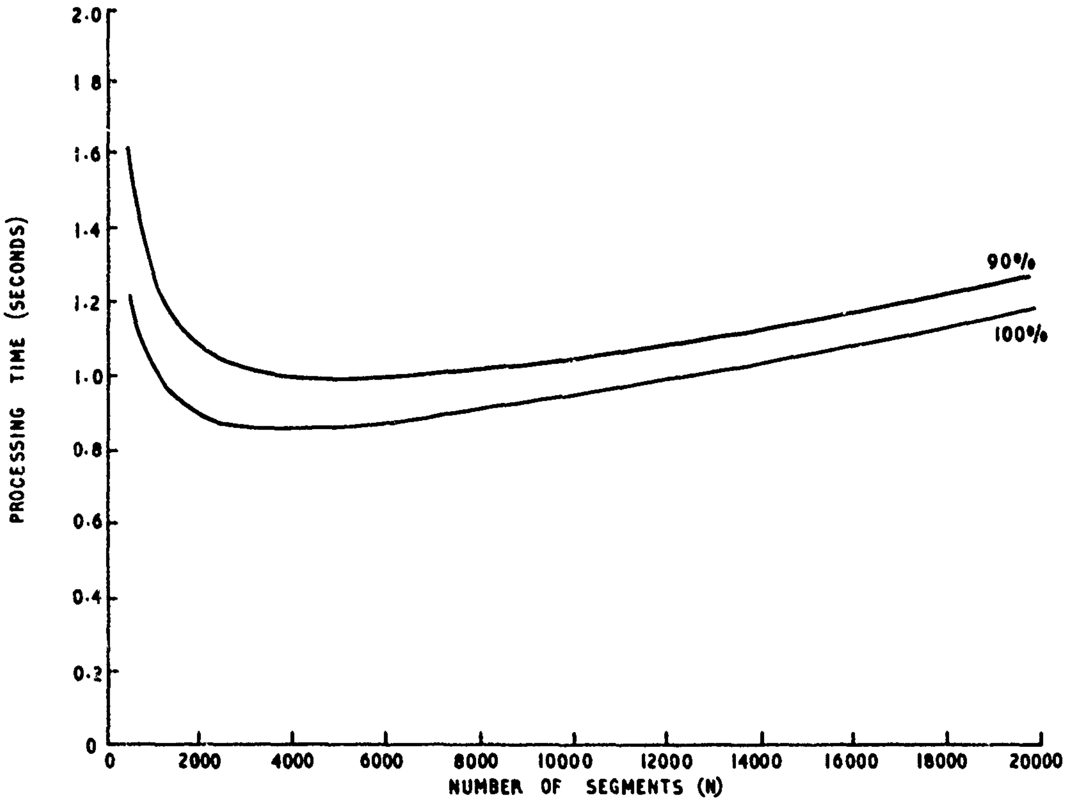

FIGURE 5 PROCESSING TIMES FOR 90% AND 100% ASSOCIATION (1000 PLOTS)

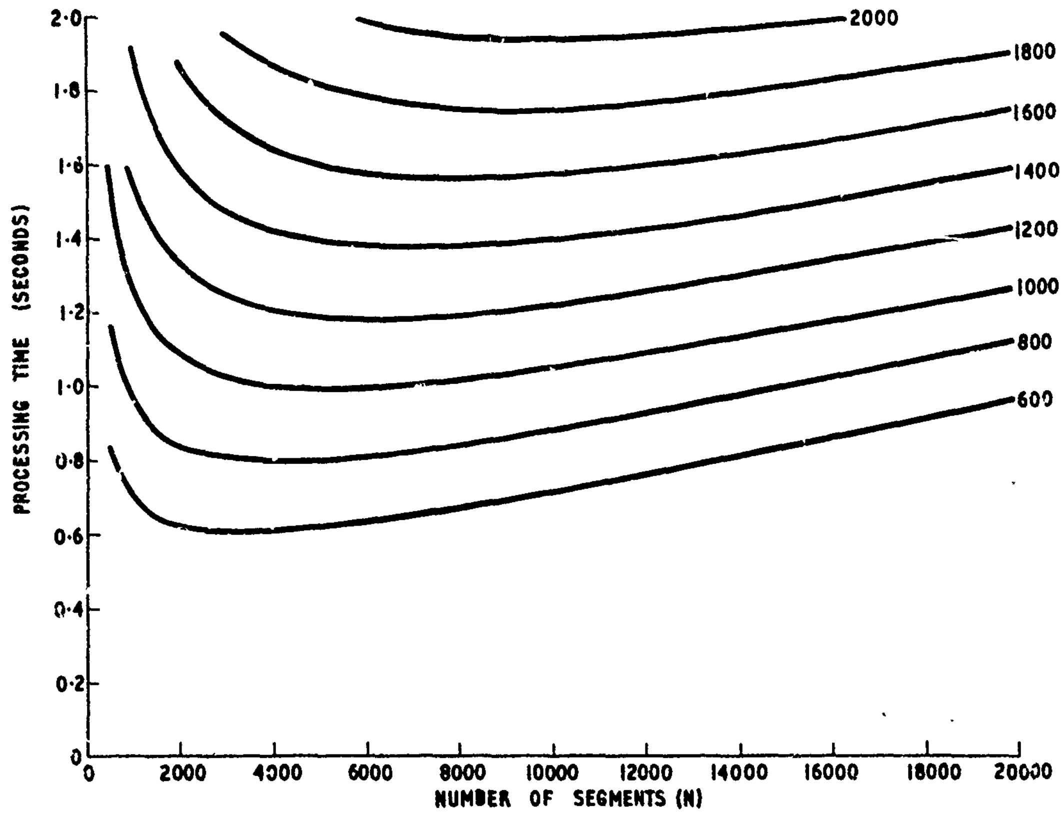

FIGURE 6 PROCESSING TIMES FOR DIFFERENT NUMBERS OF PLOTS (90% ASSOCIATION)

PARAMETER	STANDARD VALUE
RANGE CAPTURE	6 RANGE BINS
BEARING CAPTURE	1.5 BEAMWIDTHS
COUNTER INCREMENT (γ)	5
COUNTER DECREMENT (δ)	1
COUNTER INITIAL VALUE	5
COUNTER MAXIMUM VALUE (M)	15
SMOOTHING FACTOR (α)	0.3

FIGURE 7 TABLE OF STANDARD VALUES OF STATIONARY PLOT FILTER (SPF) PARAMETERS

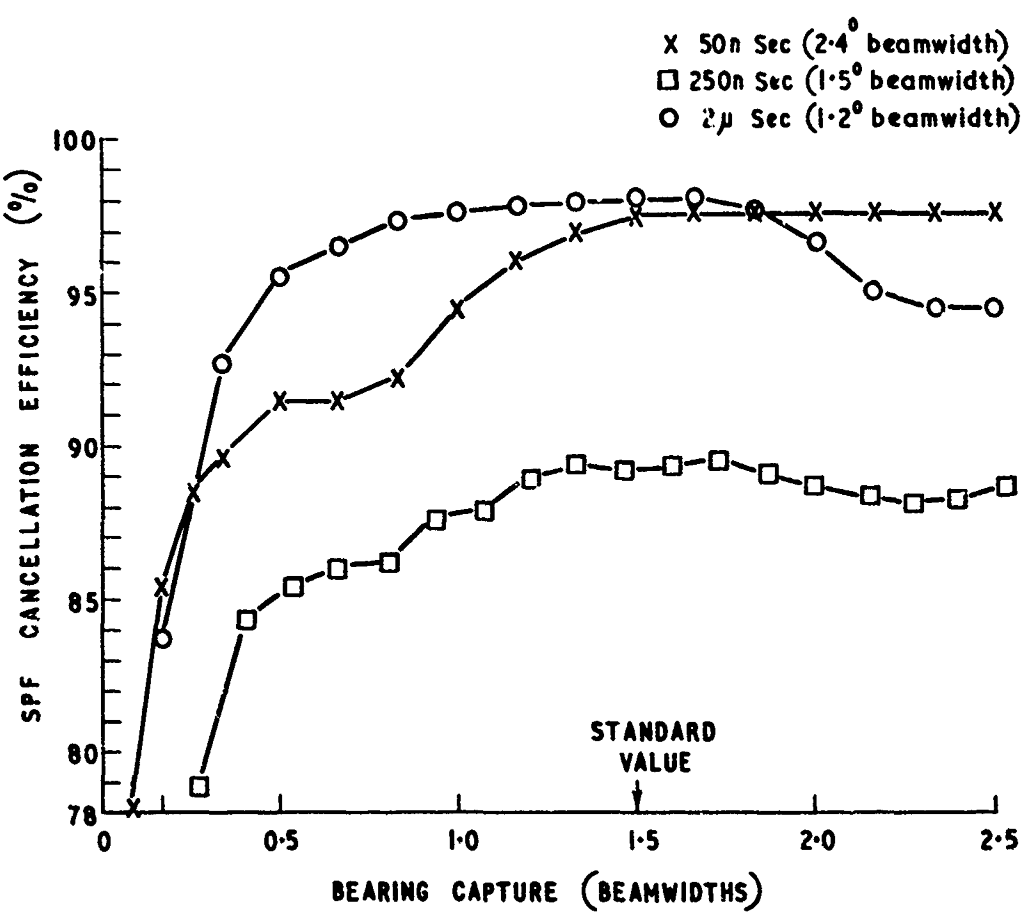

FIGURE 8 SPF CANCELLATION EFFICIENCY vs BEARING CAPTURE

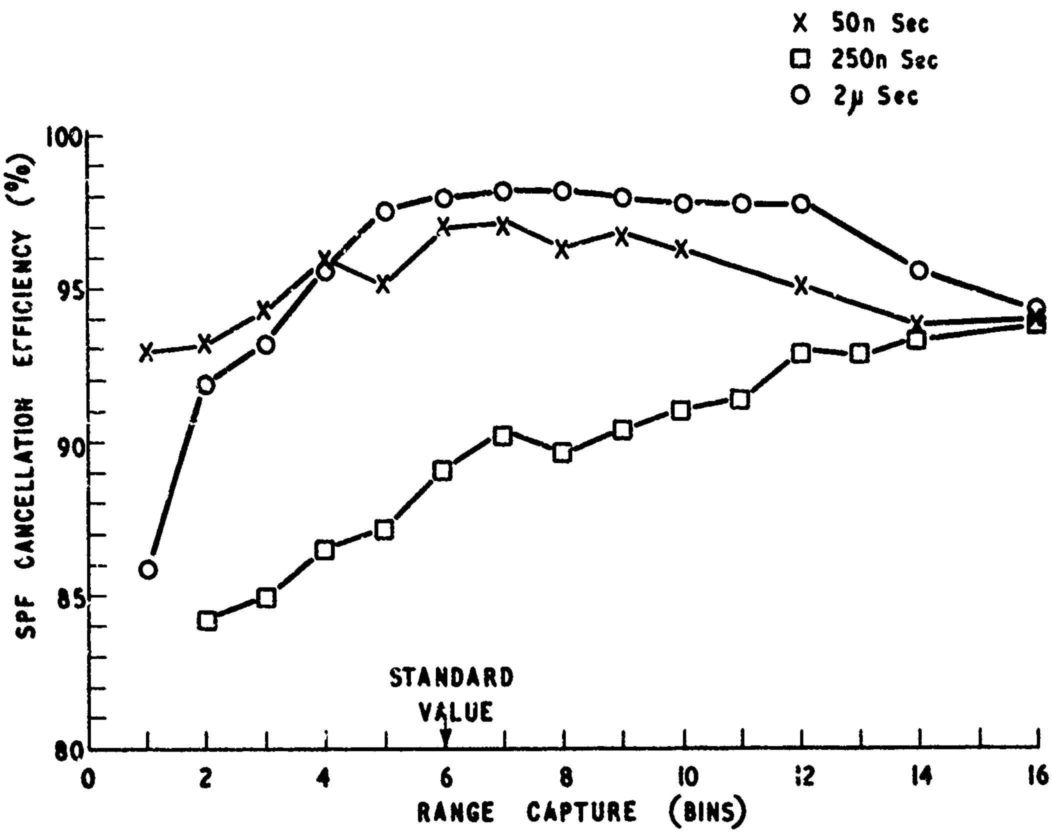

FIGURE 9 SPF CANCELLATION EFFICIENCY vs RANGE CAPTURE

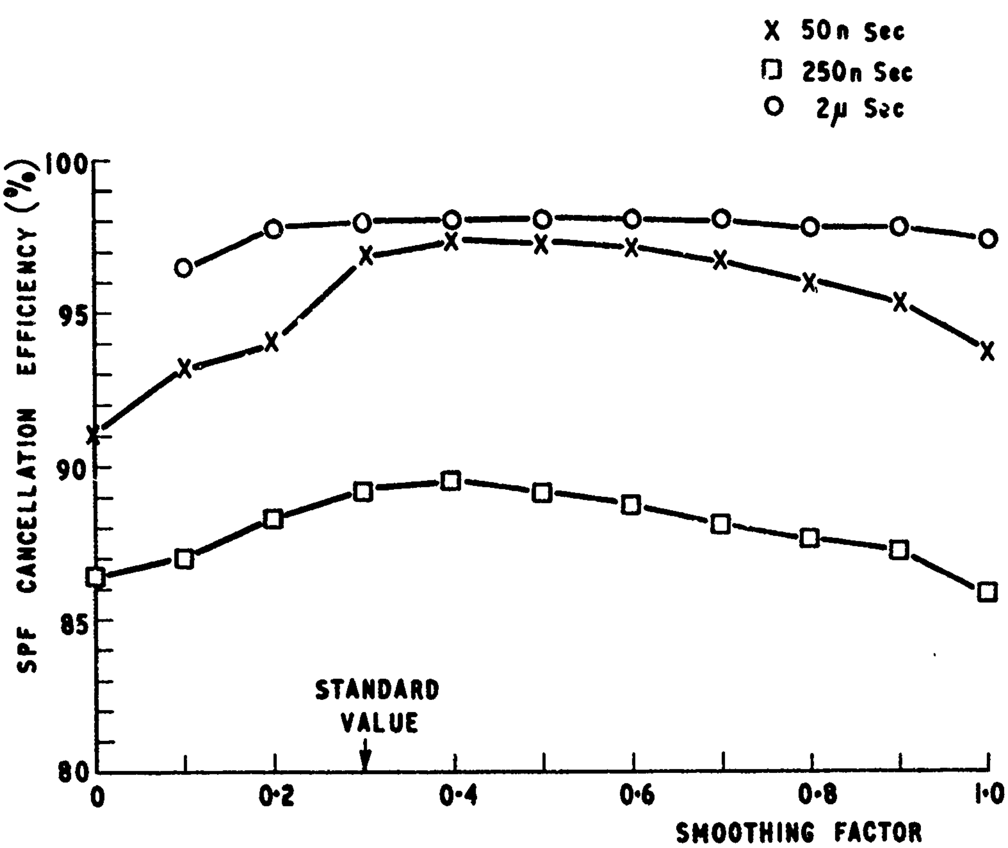

FIGURE 10 SPF CANCELLATION EFFICIENCY vs SMOOTHING FACTOR (α)

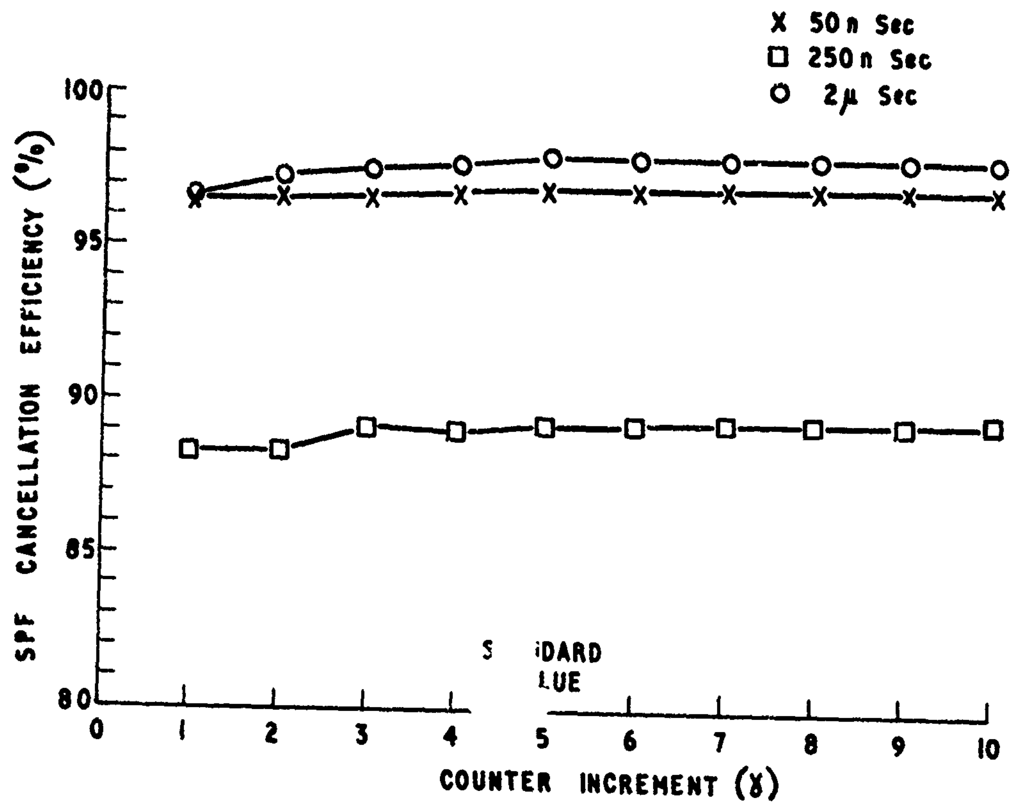

FIGURE 11 SPF CANCELLATION EFFICIENCY vs COUNTER INCREMENT (γ)

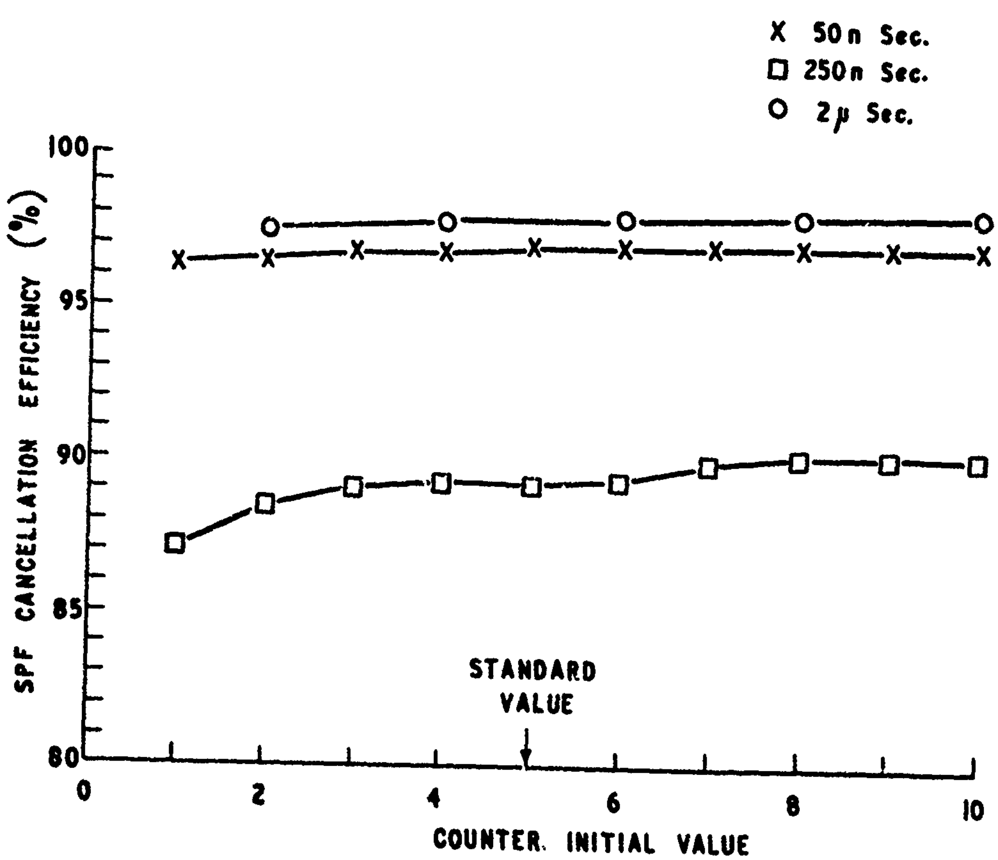

FIGURE 12 SPF CANCELLATION EFFICIENCY vs COUNTER INITIAL VALUE

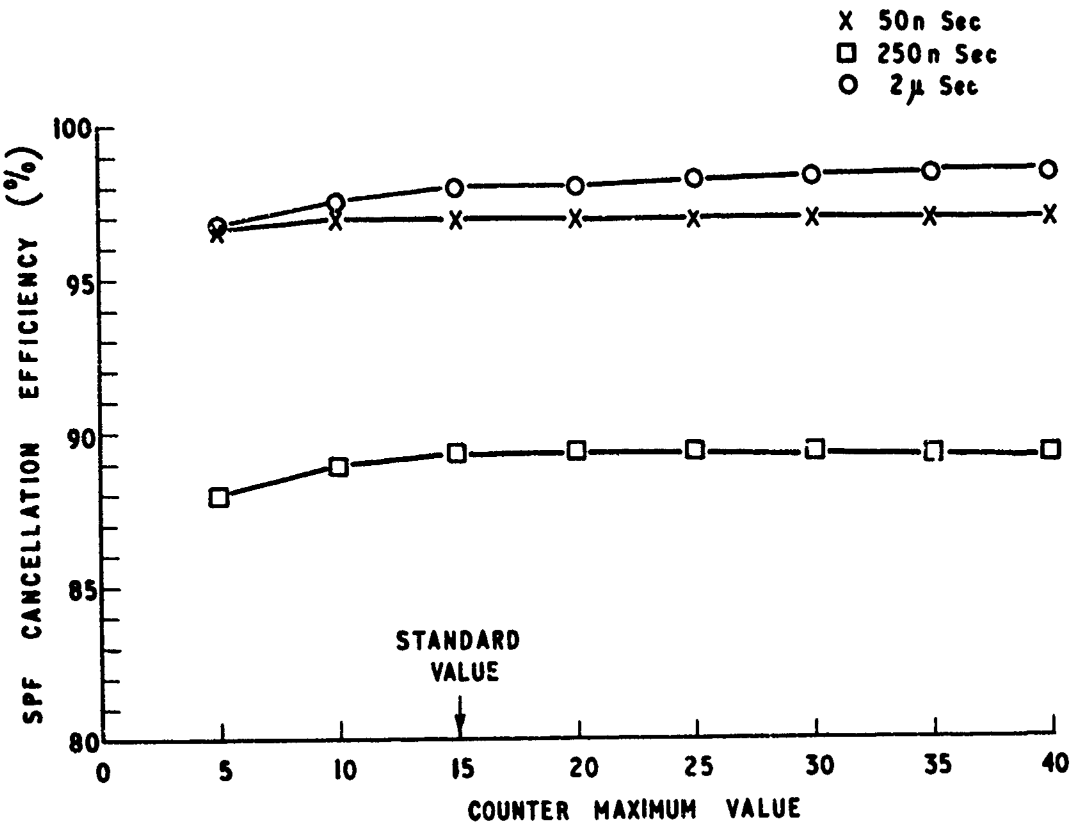

FIGURE 13 SPF CANCELLATION EFFICIENCY vs COUNTER MAXIMUM VALUE (M)

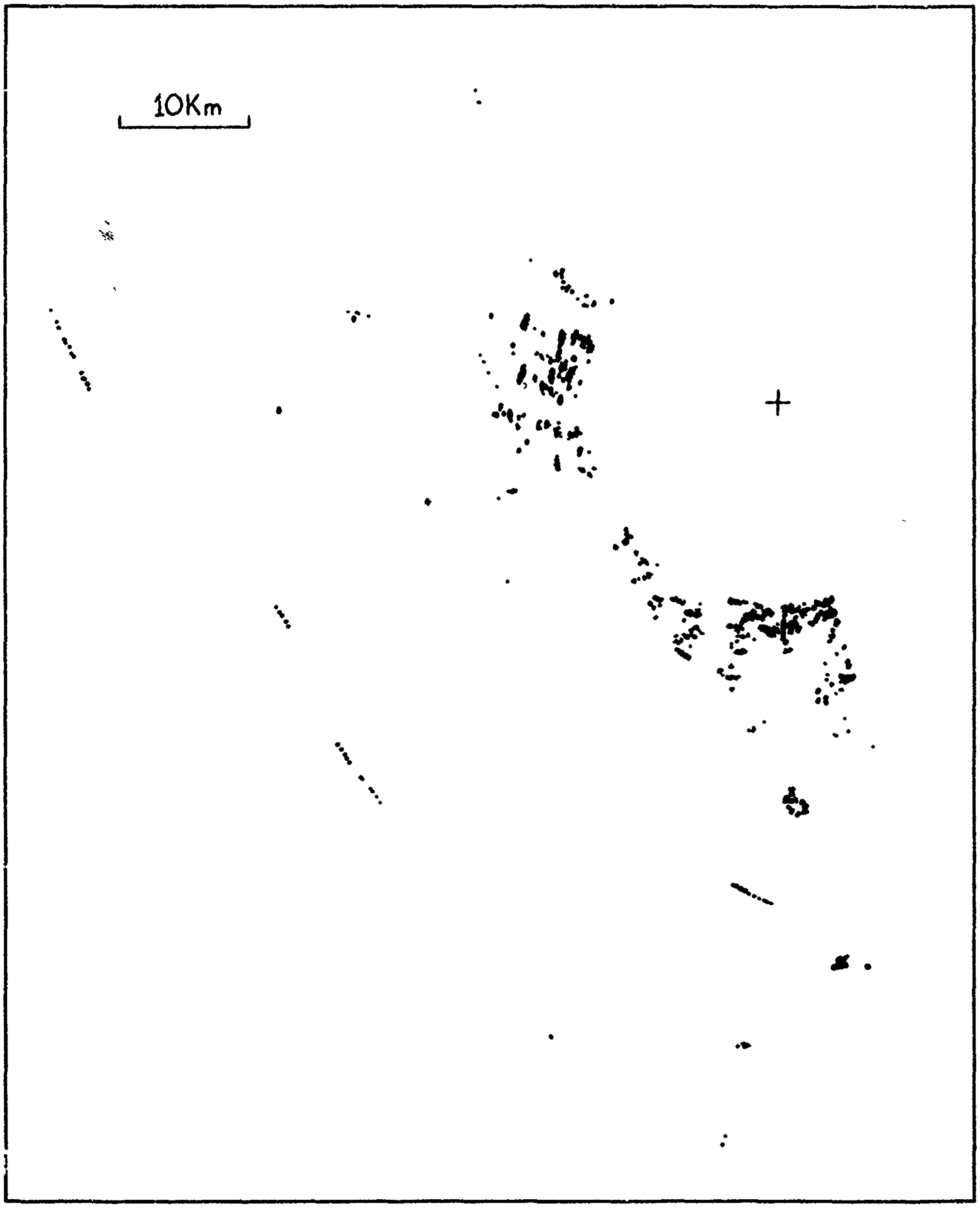

FIGURE 14 PLOTS INPUT TO THE STATIONARY PLOT FILTER (NON-MTI, 23 SCANS)

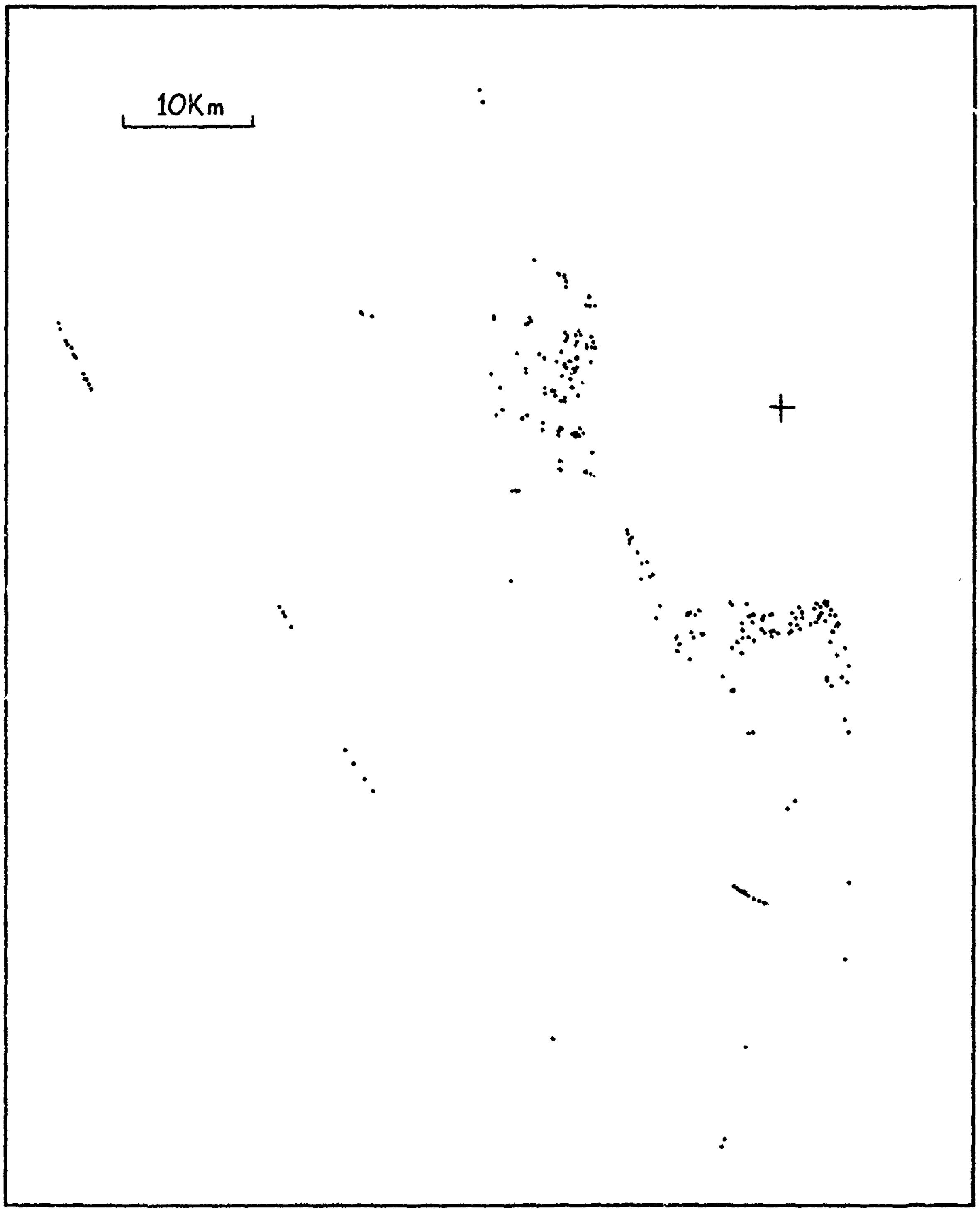

FIGURE 15 PLOTS OUTPUT FROM THE STATIONARY PLOT FILTER (NON-MTI, 21 SCANS)

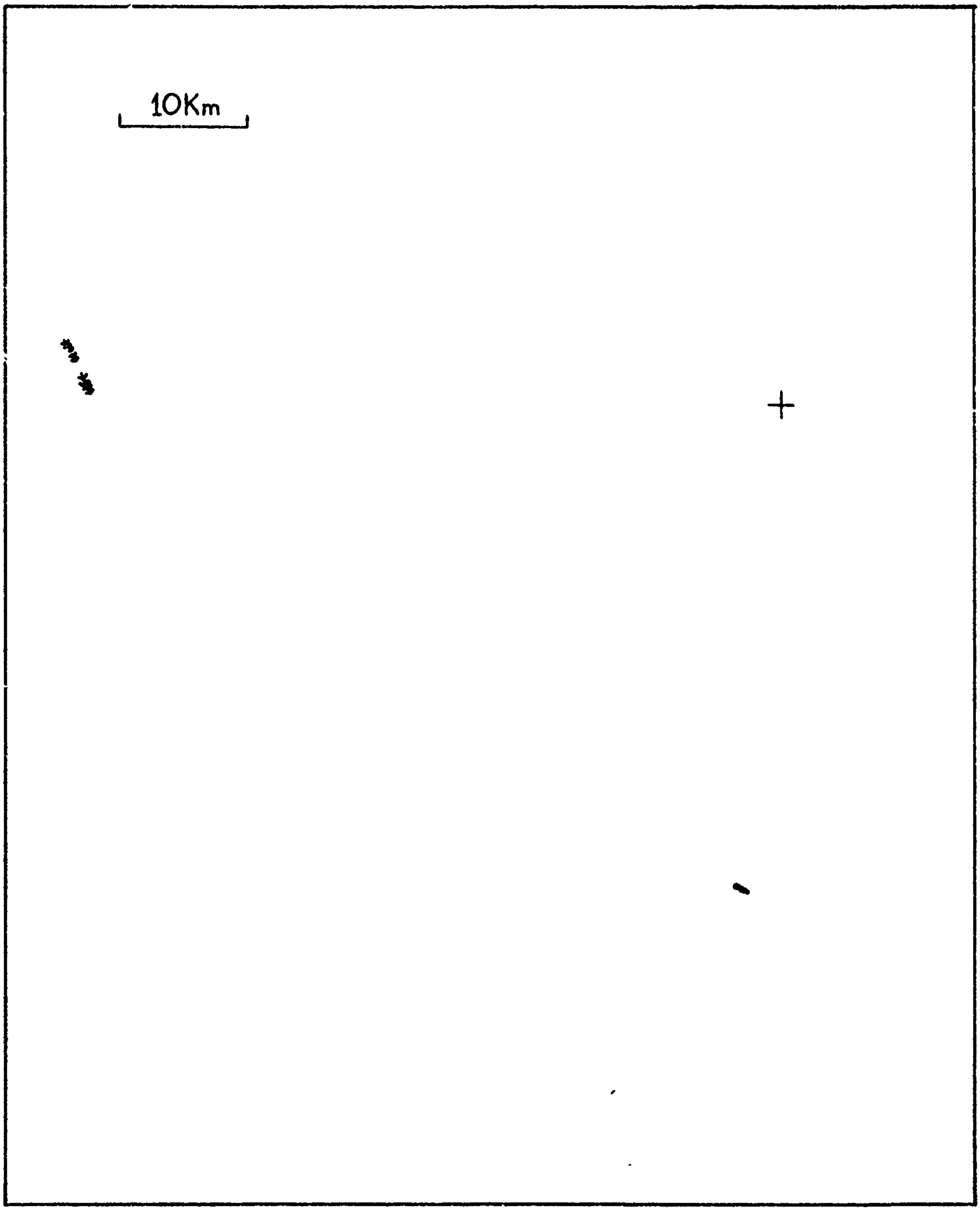

FIGURE 16 CONFIRMED TRACKS (NON-MTI WITH SPF, 21 SCANS)

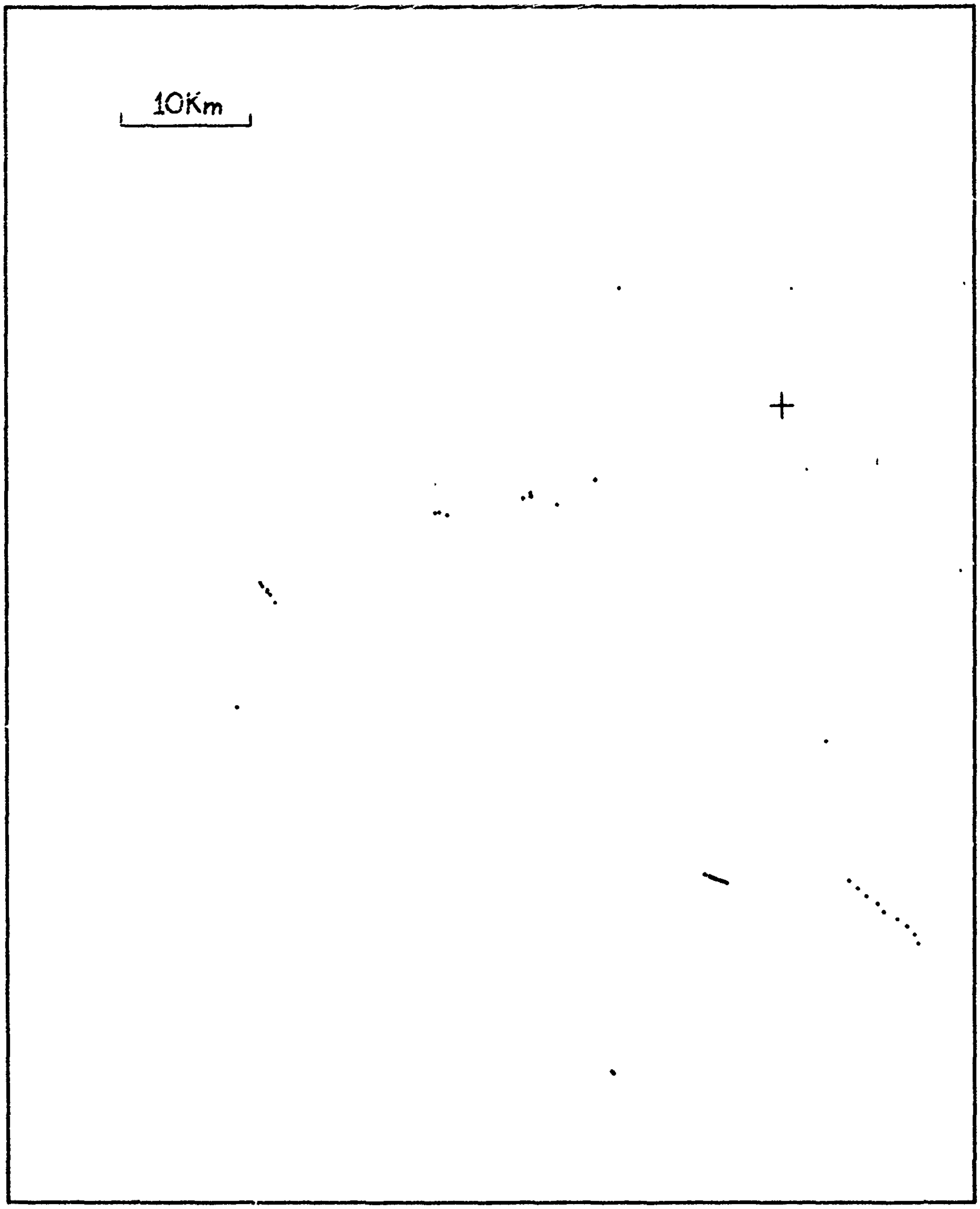

FIGURE 17 MTI PLOTS (12 SCANS)

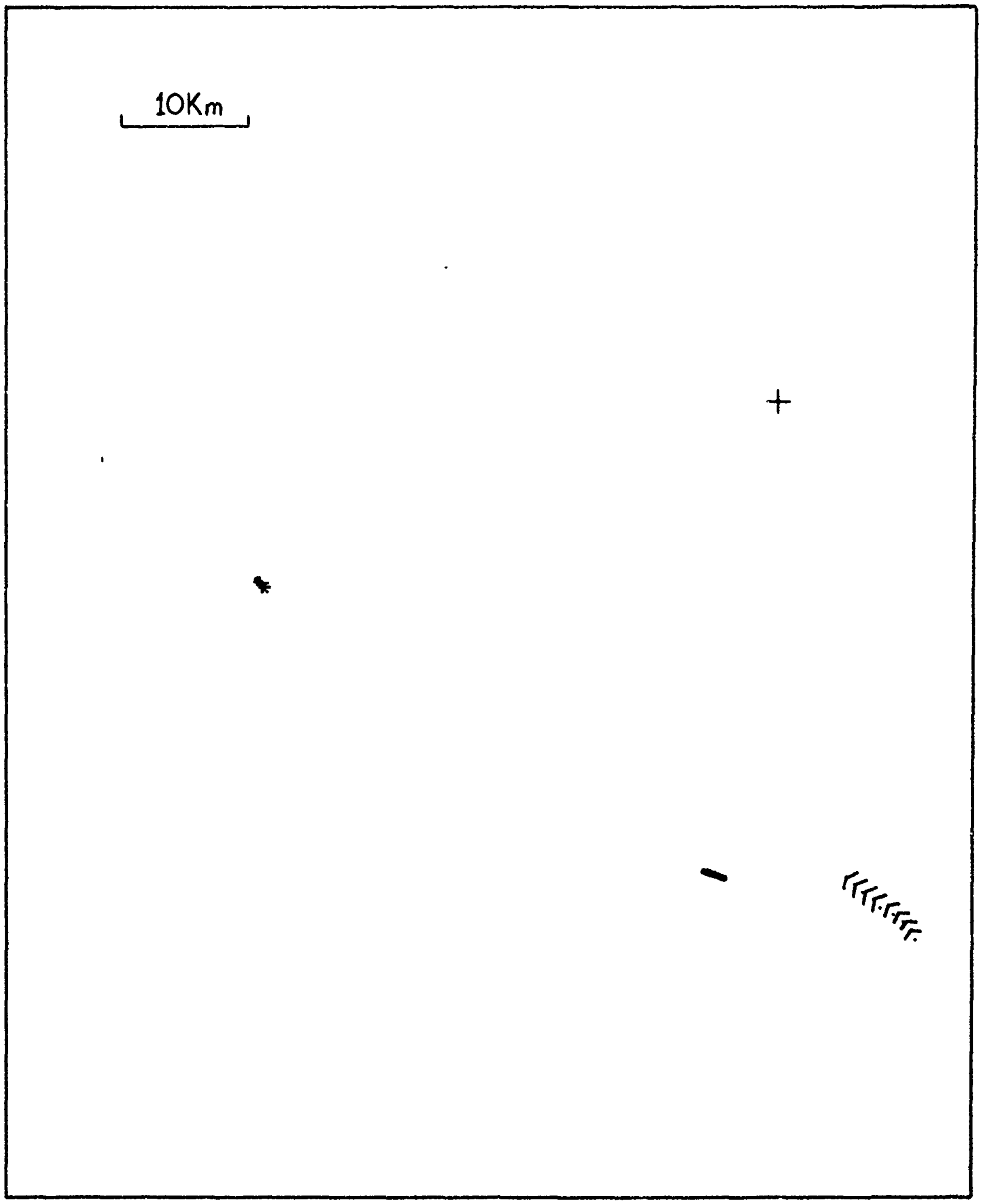

FIGURE 18 CONFIRMED TRACKC (MTI, 12 SCANS)

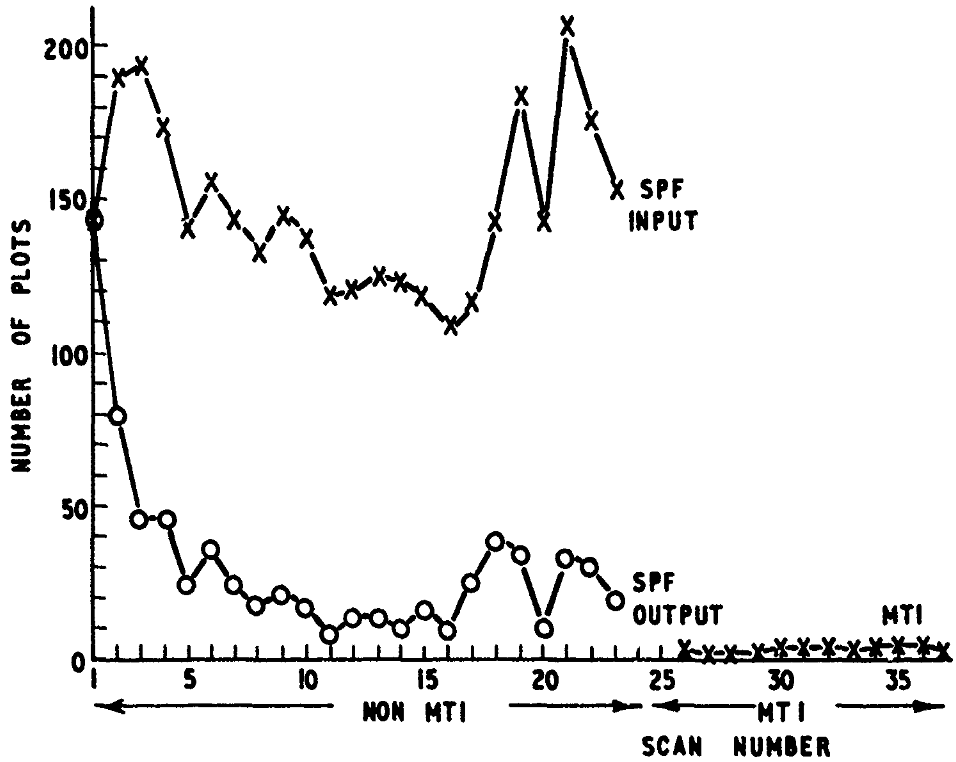

FIGURE 19 MTI, NON-MTI AND SPF OUTPUT PLOTS

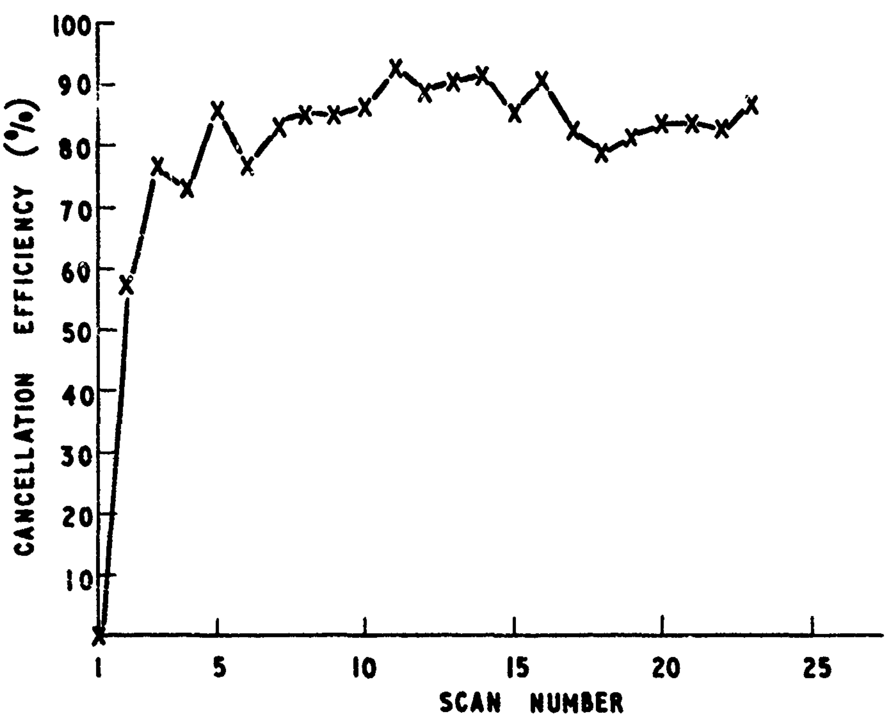

FIGURE 20 CANCELLATION EFFICIENCY OF THE STATIONARY PLOT FILTER

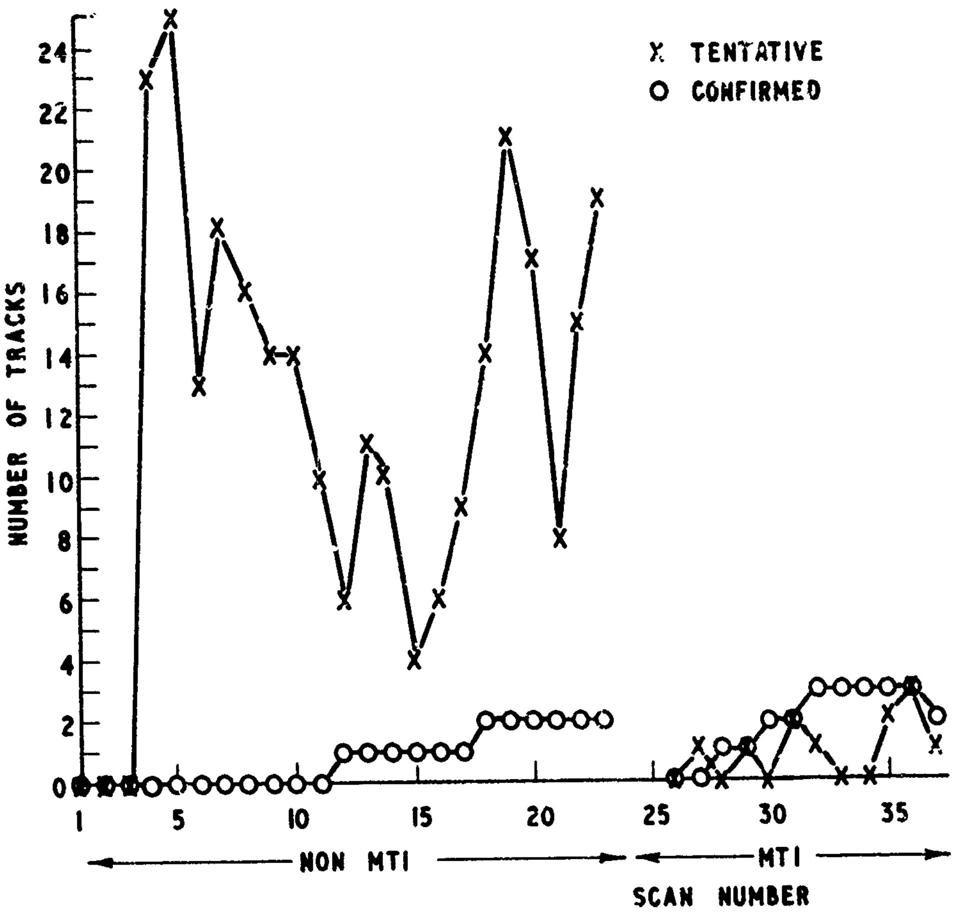

FIGURE 21 TENTATIVE AND CONFIRMED TRACK COUNTS (MTI AND NON-MTI WITH SPF)

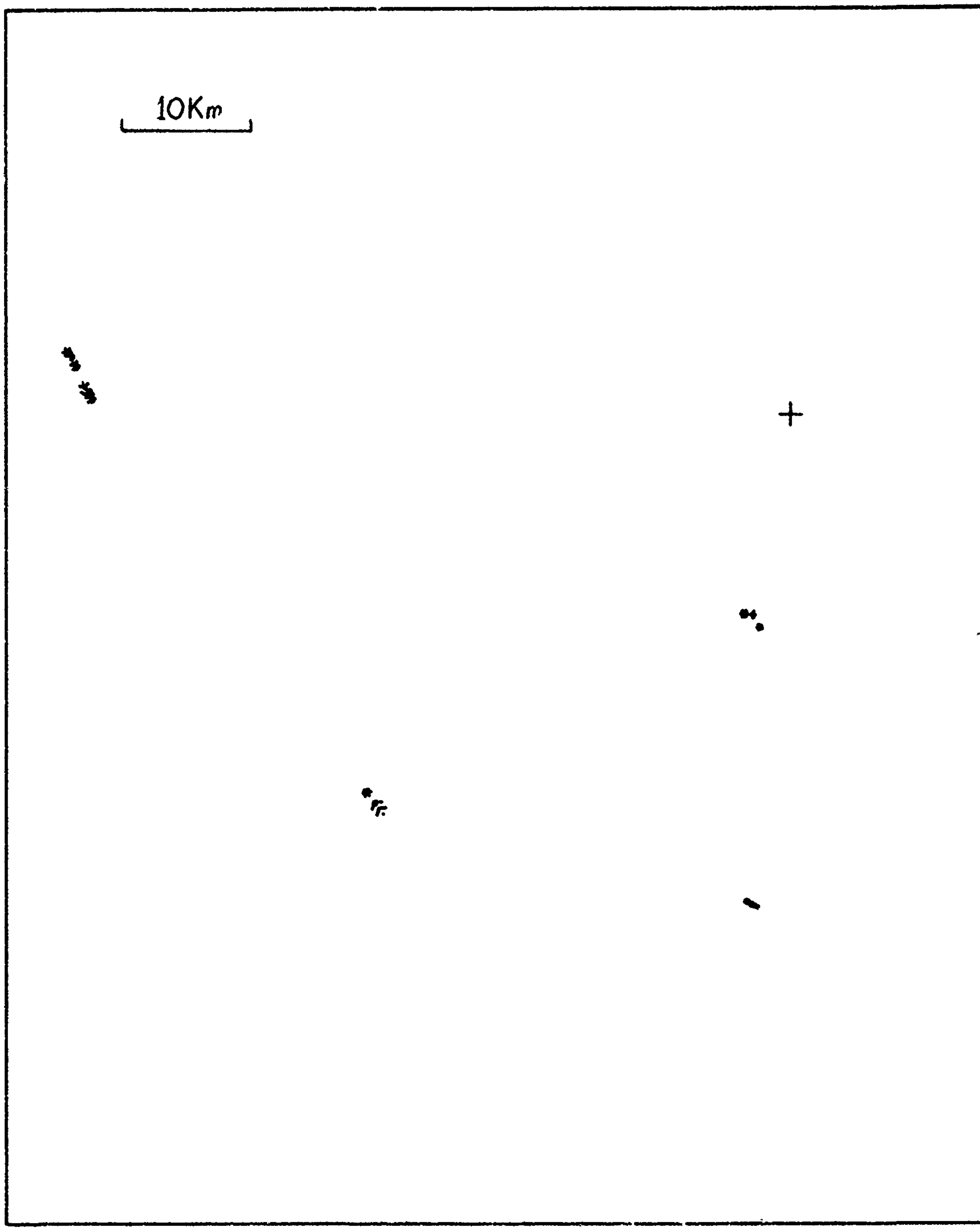

FIGURE 22 CONFIRMED TRACKS WITH REDUCED STATIONARY PLOT FILTER ASSOCIATION GATE (NON-MTI WITH SPF, 21 SCANS)

DISCUSSION

G.V.Trunk, USA
The range capture area was stated to be 6 range cells. Is this ±3 cells on each side?

Author's Reply
The optimum range capture area was found empirically to be ±6 cells, although in practice a somewhat smaller size would generally be used to reduce the speed required to escape cancellation, the optimum being relatively broad.

G. van Keuk, FRG
You are speaking of a stationary plot filter to suppress clutter at a data processing level. Could you explain what will happen in situations of nonstationary clutter? I am thinking of typical military problems with nonstationary clutter like chaff

Author's Reply
The stationary plot filter tends to blank out areas of clutter where detections which do not correlate from scan-to-scan are produced, because under these conditions the capture gates tend to overlap at relatively low clutter densities. In this case it is likely to be more beneficial to desensitize the radar in the area affected so that the plot density is reduced. It is for this reason that feedback control of the first threshold was introduced.

G. van Keuk, FRG
Could you explain what will happen if an established track enters a cluttered area?

Author's Reply
If the detection falls within the capture gate of a stored stationary plot, then it is absorbed and the track is updated for a missed observation; otherwise it is used to update the track in the normal manner.

G.Binias, FRG
What is your way of updating the clutter map?

Author's Reply
The status and position of the map entries are updated on each scan of the radar.

G.Binias, FRG
Is there a one-to-one relation between the number of resolution cells and storage cells?

Author's Reply
The size of the association gate used is a compromise between the conflicting requirements of cancellation efficiency and minimum escape speed. The size used is generally as small as possible conducive with reasonable escape speeds and is usually smaller than the resolution capability of the radar.

AUTOMATED TRACKING FOR AIRCRAFT SURVEILLANCE RADAR SYSTEMS*

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SUMMARY

An improved Moving Target Detector (MTD) (a digital signal processor) has been designed, constructed and tested which successfully rejects all forms of radar clutter while providing reliable detection of all aircraft within the coverage of the radar. The MTD is being tested on both terminal and enroute surveillance radars for the FAA. This processor has been integrated with automatic tracking algorithms to give complete rejection of ground clutter, heavy precipitation and angels (birds).

1. INTRODUCTION

In the past, difficulty has been experienced in providing high quality digital primary radar output for use in the FAA's radar tracking. However, new techniques (1,7) have been developed which significantly enhance automated aircraft detection in all forms of clutter. These techniques are embodied in a digital signal processor called the Moving Target Detector (MTD). The MTD employs coherent, linear doppler filtering, adaptive thresholding, and a fine grained clutter map to reject ground clutter, rain clutter, angels (birds), and interference. A detailed description of the ground-based radar clutter problem and solution was presented at AGARD 1976 (ref. 3).

In 1975, a hard-wired version of the MTD was tested extensively at the National Aviation Facilities Experimental Center (NAFEC) near Atlantic City. The subclutter visibility performance of the MTD on controlled aircraft flying in heavy rain and heavy ground clutter was measured to be about 100 times greater than conventional MTI. The MTD report data was found to be about 50 percent more accurate in range and azimuth than the sliding window detector. Automatic primary radar tracking was achieved when MTD processed data was input to a modified version of the FAA's ARTS-III tracker.

Recently, second generation MTD's have been designed and constructed for both terminal and enroute radars for the FAA. These MTD's (which will be tested in Burlington, Vermont, and Bedford, Virginia) are being implemented in Parallel Microprogrammed Processors (PMP's, ref. 4). These are programmable, digital signal processing computers whose high degree of parallelism was designed to give both high speed (100-150 MIPS) and great reliability and maintainability in the field.

New aircraft report centroiding and automatic tracking algorithms have been developed for use with the second generation MTD's. Because of the exceptionally clean data input to the tracker from the MTD's, it has been found that automatic tracking algorithms can be made reasonably simple. In addition to the high blip-scan ratio and the low false report rate, better tracking results from the fact that any false reports or missed detections from MTD-processed radar data are uncorrelated both spatially and temporally (ref. 6).

The paper will first describe the MTD-II system and secondly discuss the details of the automatic and adaptive track initiation and maintenance algorithms developed for these radars and, finally, present experimental results obtained when these algorithms were run on live radar data from an ASR-7 radar equipped with a PMP-2 processor.

2. MOVING TARGET DETECTOR (MTD-II) RADAR SYSTEM

2.1 General

A block diagram of the MTD-II radar system is presented in Figure 1. Analog signals from the radar's linear receiver (which is linear over 60-dB dynamic range) are sampled by 10-bit A/D coverters. This data is sent to the Parallel Microprogrammed Processor (PMP-2), a high-speed, microprogrammable, digital signal processor in which the MTD signal processing algorithms are performed. The PMP-2 outputs approximately 500-600 range-azimuth-doppler threshold crossings per scan out of the 3,000,000 cells in the radar. Typically, there are between 5-15 threshold crossings per aircraft target. These threshold crossings are sent over the IEEE bus to the post-processor where report correlation and interpolation are done on a single-scan basis. In addition, post-MTD area thresholding and scan-to-scan correlation are performed to remove the few false reports that are sent by the PMP-2 signal processor. Aircraft position reports are then sent from the post-processor to a digital maintenance display and over an interface to the users displays. It should be noted that five computers are interconnected asynchronously via the IEEE 488 bus. They are:

1. PMP-2 Signal Processing Computer
2. Radar Controller (Intel 8080)
3. Post-Processor (Data General Eclipse S-130)
4. Digital Maintenance Display (Data General Nova 3/12 based)
5. IEEE Bus Controller (AMD-2901)

2.2 Parallel Microprogrammed Processor (PMP-2)

2.2.1 Introduction

The Moving Target Detector (MTD) signal processing algorithms are performed in a programmable digital signal processing computer designed at Lincoln Laboratory called the Parallel Microprogrammed Processor, ref. 4.

*The work reported was prepared for the Federal Aviation Administration under Interagency Agreement DOT-FA-72-WAI-242 and DOT-FA-TQ-679 by Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology under Air Force Contract F19628-78-C-0002.

The second generation MTD radar systems were designed for use in an environment of operational FAA terminal and enroute radar sites. These requirements indicated a need for a flexible processor, one that is:

1. capable of self-diagnosing failures,
2. easily maintainable,
3. fail-soft in its performance,
4. easily modifiable,
5. expandable and completely programmable so that it can be applied to a variety of radar signal and data processing tasks.

Figure 2 is a block diagram of the PMP. It consists of several Processing Modules (PM's) in parallel connected together by four busses. Each PM contains input memory and auxiliary memories appropriate to the radar processing job, together with a Processing Element (PE) which performs all of the arithmetic functions. The PE is connected to the input and auxiliary memories via a local PM memory bus.

Functions performed within the PMP are divided into two types. The data handling and arithmetic functions are performed in the PM's and the program control functions are performed for all PM's within the controller.

2.2.2 Description of the Processor Element (PE)

The heart of the PMP-2 is the Processor Element (PE). Each PE is rated at approximately 25 MIPS and several can be paralleled to provide processing capability in the hundreds of MIPS.

Figure 3 shows the block logic diagram of the PE. With operands in the five registers (A1, B1, M, A2 and B2) at the start of a cyle, control lines are set true or false to control the operations performed in the two ALU's, the random access memory and the word shifters. At the end of the 75-nsec cycle time the data is ready and the five registers are strobed to accept the new results. The input or output registers might also be strobed at this time. All data are 24 bits wide.

The PE can perform all of the basic arithmetic functions such as add, subtract, AND/OR, bit-by-bit multiply, divide, fixed to floating, floating to fixed, etc. It also contains special hardware to compare A1 and B1 and set flip-flops, take the absolute value to B2, and take the larger or smaller of A1 or B1.

The lower part of Figure 3 shows the local PM data bus which is connected to the PM memories and/or to the Data Interchange Bus (DIB).

The PE is programmed to do all of its possible operations in parallel during one cycle. It is thus often performing six operations during one 75-nsec period. It uses space equivalent to 240 16-pin IC's. The PE board requires power wiring plus 126 pairs of wires for data connection. The PE must all reside on one board to be able to perform at its rated speed.

2.2.3 Controller

The controller is broken into two parts, the program memory and the controller proper. Initially for each application, the program memory is a RAM which is loaded from the standard interface bus. Later this RAM will be replaced directly with a ROM.

The controller performs the following functions:

1. Interrupts by a priority, vectored, maskable interrupt system.
2. Indexing to modify all memory addresses.
3. Loop counting.
4. Subroutine control.
5. PM logical addressing. Each PM has a physical and a logical address. If one PM is diagnosed to be defective, it can be replaced by changes in the logical addresses of one or more PM's.
6. PM state generation. Data paths can be varied throughout the PMP-2 to control the transfer of data between input and auxiliary memories and the PE. Also, data can be transferred between PM's and the controller. The PM state is also used to turn on and off certain functions selectively within the PM's.
7. Standard bus interface. The controller contains an interface to the standard interface bus described in IEEE Standard 488-1975.

2.2.4 Input and Auxiliary Memories

The size of these memories depend on the particular PMP application. Three different types of memory boards have been constructed using MOS static RAM IC's. All memories have been mounted on the standard plug-in boards. The memory boards require power connections plus up to 72 pairs of wires for data transfer.

2.2.5 Software

A comprehensive instruction set for both the controller and the PE has been written to program the PMP. A cross assembler is used on an IBM-370 computer to write, debug and assemble code. The IBM-370 is connected to a NOVA 3/12 minicomputer which is in turn connected to the PMP via the IEEE bus. A debugger has been written for the NOVA to facilitate examining and debugging code in the PMP.

2.2.6 Hardware Implementation

The PMP's are constructed using Schottkly TTL logic. The first three were built at Lincoln Laboratory. These are designated PMP-1. The next seven are being built by Stein Associates and are designated PMP-2. The PMP-2's have a slightly expanded instruction set, minor hardware design dfferences, and are packaged differently. The PMP-2's are being used in terminal and enroute radar systems. A photograph of the PMP-2 being used with the terminal ASR-7 radar is shown in Figure 4. This PMP-2 consists of seven PE's, six of which will be in constant use and one spare. The PE's are each on one Augat board with 296 16-pin DIPs. The controller proper and program memory are each on one board. Also, the auxiliary and input memories are combined on one board. Finally, there is one board for the front panel interface. As can be noted in Figure 4 there are five extra boards; a front panel interface (2), controller (1), PE (1), and auxiliary memory (1). These constitute a separate PMP which will eventually be used to replace the S-130 minicomputer as post-processor when the post-processor algorithms are microcoded.

2.3 MTD-II Signal Processing Algorithms

2.3.1 General

Signal processing algorithms used in the PMP-2 are generally the same as those used in MTD-I. However, the doppler filters used in the MTD-I (see ref. 1) are not being used. Instead, an approach is used which employs generalized transversal filters as opposed to the Discrete Fourier Transform. The transversal filters give better doppler filter sidelobe performance. This approach is also used to generate the zero radial velocity filter. The samples used to generate the mean-level thresholds include neither the cell being thresholded nor the cells on either side in range. The clutter map has one cell for each range-azimuthal cell (3-dB beamwidth) as opposed to one cell for each range-CPI cell as in MTD-I.

The original filters for the MTD-I consisted of a cascade of three separate filters; a three-pulse canceller, an eight-point FFT, followed by weighting in the frequency domain. In that processor ten pulses were processed into eight filters. The zero radial veolocity filter was obtained by adding the ten complex samples, five at a time, taking the magnitudes and then adding the two magnitudes. In the MTD-II the doppler filters have been synthesized by cascading a two-pulse MTI canceller and a set of eight filters (see Figure 5).

2.3.2 Zero-Velocity Filter Design

The design criteria for the zero-velocity filter is to maximize uniformly the filter gain across the portion of the doppler space not covered by the non-zero doppler filters while keeping sidelobes low in the stopband. An equi-ripple filter design was used. The program (see ref. 8, pages 187-204) solves the optimal linear phase finite impulse response filter design by formulating a Chebychev approximation problem, and solves this problem by use of the Remez multiple exhange algorithm. The filter impulse response is then calculated, and since we are dealing with a linear time invariant system, the impulse response completely characterizes the filter. By scaling the impulse response to the desired bit truncation, these results are used as the zero-velocity filter weights. The filter shape is presented in Figure 6.

2.3.3 Non-Zero Doppler Filter Designs

These filters were designed using the optimum processor filter design method of DeLong and Hoffstetter (ref. 2). The details of the design are presented in ref. 5. These filters are preceded by a two-pulse MTI canceller because it was found that the number of bits in the transversal filter weights dropped markedly by preceding the filters with the two-pulse canceller. With this technique the filter weights need only be 3 or 4 bits plus sign. Figure 7 presents the MTI improvement factor vs. doppler frequency for four of the seven non-zero filters. Filters 1 and 7, 2 and 6, and 3 and 5 are mirror images of each other. These filters have doppler sidelobes approximately 10 dB lower than the MTD-I filters. This should give the system even better performance in rain than the first MTD. In addition, the MTI loss of these filters is less than those of MTD-I.

2.3.4 Waveform Design

The MTD-II uses a multiple PRF scheme as in MTD-I for the terminal radar (ASR-7). A group of eight pulses whose spacings are 900 μsec is alternated with a group of eight pulses whose spacings are 1100 μsec. These correspond to PRF's of 1111 Hz and 909 Hz respectively. Each group of eight pulses which are processed coherently together is called a Coherent Processing Interval or CPI.

3. POST-PROCESSING ALGORITHMS

3.1 General

The post-processing algorithms consist of three functions (see Figure 8); report correlation and interpolation, post-MTD thresholding, and scan-to-scan correlation. Post-MTD thresholding is an area CFAR (Constant False Alarm Rate) thresholding algorithm which deletes false alarms primarily due to angels (birds). It is the function of correlation and interpolation to cluster (combine) all range-azimuth-doppler threshold crossings which are caused by the same aircraft, and combine them together into a single report with the most accurate radar observables (range, azimuth, doppler velocity, strength). Finally, scan-to-scan correlation deletes those uncorrelated radar reports due to noise, automobile traffic, and angels whose scan-to-scan histories indicate characteristics unlike those of aircraft (i.e., low speeds or lack of spatial correlation from scan to scan).

3.2 Correlation and Interpolation

It is the purpose of these algorithms to cluster together those range-azimuth-doppler threshold crossings which are due to one target (i.e., a bird, aircraft or automobile) and then to calculate from the data of the cluster the best value of radar observables for the target. These radar observables are range, azimuth,

doppler velocity and strength. The criteria used for clustering is range and azimuth adjacency of the threshold crossings. The strength of each of the threshold crossings is normalized depending on the gain of the doppler filter from which it came. The range and azimuth are calculated by weighting both the range and azimuth by the strength (voltage) associated with that threshold crossing. The doppler velocity is calculated by interpolating between the doppler cell with the largest strength and its adjacent doppler cell with the second greatest strength. This interpolation is done to one part in 64 across the band of eight doppler cells.

3.3 Post-MTD Thresholding

Post-MTD thresholding is an area CFAR technique to delete single CPI false alarms due to residual angels, interference and weather clutter that are not removed by the signal processing algorithms in the PMP-2 signal processor.

With this scheme, the coverage out to 48 nmi is divided into cells corresponding to an area 4 nmi in range and 22½° in azimuth. The doppler dimension corresponds to the doppler filter number (between 0 and 7). The last range cell extends in range from 48 nmi to 60 nmi and has the same azimuthal and doppler extent.

Any radar report cluster containing only one threshold crossing or a cluster at short range (less than 16 nmi) with two threshold crossings causes the threshold of the cells to be increased. For each report in these clusters that exceeds the current threshold value, a fixed increment is added to the threshold. At the end of each scan, any threshold which was not incremented this scan has its value lowered by a fixed decrement. The magnitude of the decrement is less than the increment and varies with doppler number.

In addition, if the number of single CPI reports per 11¼° wedge (for all ranges) exceeds 10, then those reports will not be used to initiate tracks in the scan-to-scan correlator and the post-MTD thresholds will not be updated for that area.

3.4 Scan-to-Scan Correlation

3.4.1 General

The scan-to-scan correlator is a radar report editing process. It does not change any radar report data, it only deletes some of the data which is input to the scan-to-scan correlator. It is the purpose of these algorithms to delete all reports due to non-aircraft phenomena and pass all reports which are due to aircraft. A block diagram of the scan-to-scan correlator is presented in Figure 9. This process may be divided into six functions as follows.

1. Associate track files* with radar target reports,
2. Resolve target track file association ambiguities to one target for each track file,
3. Test and update track file parameters and radar observables with new radar report data or set track coast parameters if no radar data is present on this scan,
4. Delete track files if radar data is not present for several scans,
5. Output radar report data to digital display. Display if track file "Quality" parameter exceeds a threshold, and
6. Test to initiate track files on radar reports not associated with tracks.

The preceding processing steps are performed 32 times per scan of the radar. That is to say, radar data is collected into a buffer and the scan-to-scan correlation programs sequentially process the data for 11.25° sectors (11.25° x 32 = 360°). Because of problems caused by the ability of aircraft to cross these sector boundaries, the processing of the data at different stages has different sector delays relative to the sector of radar data being presently input to the scan-to-scan correlator. The program structure delay is at present a total of eight sectors. A breakdown of the delay for each function is presented in Table I.

TABLE I

Function	Delay (relative to radar sweep)
Target-track association	3 sectors
Resolve target-track ambiguities	5 sectors
Update track files	5 sectors
Delete track files	5 sectors
Output data to display	5 sectors
Initiate track files	8 sectors

Next will follow a detailed description of each of six sequential functions performed by the scan-to-scan correlator.

---

*A track file is a set of radar observables which contain the position and velocity components of past radar report data as well as other past data derived parameters which signify relative confidence that the track file is caused by aircraft or by non-aircraft radar returns (e.g., cars, birds, etc.).

3.4.2 Association of Radar Target Reports With Track Files

The first processing to be done is to associate radar target reports with existing track files. This is done by setting up a search area in range and azimuth for each track. This circle is centered around its "predicted position". The predicted position is the calculated expected position of the radar report on the current scan. The predicted position is calculated differently depending on the scan life of the track either when the track file is initiated or subsequently when the track file is updated.

After targets have been associated with tracks, there will frequently be more than one target associated with several of the tracks, and some of the targets will be associated with more than one track before reduction of these multiple associations to unique one track/one target associations. A list of the target associations is made for each track. The output of the target-to-track association is this list.

3.4.3 Resolution of Target Track Association Ambiguities to a One Track/One Target Relationship

It is the purpose of this section of the scan-to-scan correlator to reduce the multiple target/track associations to one track/one target associations. The first step in this process is to examine each track which is associated with one or more target reports. If the track is associated with only one target and the target is associated with no other tracks, then the track and target are one-to-one related. One track/many target associations are resolved by using an algorithm which takes into account the distance between each of the targets and the predicted track positions and, in addition, the total number of range-azimuth-doppler threshold crossings in the radar report. Many track/one target associations are resolved by use of the track "Quality"* parameter. Tracks with the highest "Quality" are given preference.

If two tracks, each with high "Quality" are competing for two targets, the following quantities are calculated:

$$D_1^2 = d_{11}^2 + d_{22}^2$$

$$D_2^2 = d_{12}^2 + d_{21}^2$$

where d_{11} = distance from track 1 to target 1

d_{21} = distance from track 2 to target 1

d_{12} = distance from track 1 to target 2

d_{22} = distance from track 2 to target 2

If D_1^2 is less than D_2^2, then track 1 is assigned with target 1 and track 2 with target 2. If the converse is true, the assignment is reversed.

3.4.4 Updating of Track Files with New Report Data or Coasting of Tracks

Once unique target-to-track associations have been made, the track files may be updated to predict ahead where the aircraft report will be on the next scan. Different prediction algorithms are used depending on the "Quality" attribute of a track. Newly initiated tracks are predicted to be in their initial position with zero velocity. All tracks with low "Quality" or low track life are updated using a linear extrapolation from the last two measured points. Those tracks whose "Quality" or track life are high are extrapolated using an $\alpha - \beta$ tracker.

Several speed checks are performed for tracks with low track life and low "Quality". Any which fails any of the speed checks is coasted. The first check is made for "azimuth jitter". This exists when the measured azimuth change is opposite in sign to that expected, and the change in range is zero. For these tracks the consistency of the track speed is checked. All tracks are tested for a speed below 60 knots and any track below these speeds fails the speed check and is coasted.

Tracks which have not been updated in this scan are tested for possible coasting instead. The two requirements for this are that the track have high "Quality" and have not been coasted too frequently in recent scans.

3.4.5 Deletion of Tracks from Track Files

Track files are deleted (dropped) by first going through all tracks and seeing if the "Quality" is negative. This negative "Quality" has been set in the track updating section of the algorithms if the track is to be deleted Deletion is accomplished solely by removing the track number from the track pointer lists and adding the track number to the list of unused track numbers.

3.4.6 Elimination of Low or Irregular Speed Reports from Display

In order to eliminate low-speed (automobile clutter breakthrough) reports from being displayed a set of algorithms was addded to the scan-to-scan correlator. These track files whose reports are of low or irregular speed are maintained, but never displayed. This significantly reduces the initiation of new tracks caused by clutter breakthough or automobiles. The handling of this is described below.

---

*"Quality" is a track parameter which is a running sum of the number of CPI's of the targets associated each scan (e.g., if on succeeding scans a track is started and updated with reports whose number of CPI's is 2, 1, 3, 2, 4 on five succeeding scans, then the track "Quality" on each of those scans will be 2, 3, 6, 8, 12.

The association circle size used for a track which has been identified as failing the speed checks has a circle corresponding to the distance an aircraft would go in one scan at a speed of 180 knots. The purpose of this is to prevent such a track from associating with targets away from its immediate area.

The first time a track fails the speed checks it is flagged and will not be displayed. On each successive scan, during which it is assigned a target, this process is repeated.

In addition, the center of the search circle is reset to its value when the track was first identified as failing the speed checks. These tracks are not dropped, instead they are coasted until the coast counter reaches a threshold.

3.4.7 Transmission of Displayable Radar Report Data to Digital Display via IEEE Bus

It is the purpose of this function to decide whether tracks are of sufficient "Quality" that the radar report data associated with them or their coasted position may be displayed. The decision is made as follows.

1. All reports whose track files have "Quality" greater than five are displayed.
2. Reports whose track files have "Quality" greater than three and range greater than 20 nmi are displayed.

All radar reports whose track "Qualities" pass either of these criteria are then sent out on the IEEE bus. The radar observables sent out are track number, position of radar report and coast indicator. The data is output one sector at a time.

4. RESULTS

As of this writing, the terminal ASR-7 MTD system is in the final stages of test and evaluation before shipment to Burlington, Vermont, where it will undergo testing in an operational environment. A photograph of this system is presented in Figure 10. The system sensitivity has been tested with a coherent test target generator and measured to be within experimental error of the expected value. The PMP processor operates out to the full instrumented range of 60 nmi. Tests on aircraft targets of opportunity have been made. Figure 11 presents two photographs of the digital maintenance display output at 10-scan intervals. Radar reports from the present scan along with scan histories are displayed. The aircraft are solidly detected as was the case with MTD-I. At close ranges where there is much automobile traffic visible to the radar, data was also collected. These results are shown in Figure 12. The aircraft which are taking off and landing at Hanscom AFB, an airport about 1/2 nmi from the radar, are detected clearly and no detection from the automobiles on a nearby highway are seen. Later, tests were made where a fast moving intense weather front passed through the area. The intensity of the rain was measured to be near the top of A/D converters (greater than 40 dB). Aircraft were clearly detected as they passed through the weather front (see Figure 13). Few, if any, false reports were observed after the scan-to-scan correlator processing.

Initial accuracy tests have been performed using four targets of opportunity. The trajectories of the aircraft tracks were as follows: two flying radially; one tangentially and one a combination of radial and tangential motion. Ten scans of range and azimuth data were fit to a straight line using the method of least squares and the deviation from that straight line calculated. The aircraft chosen were flying in straight trajectories. Since 10 scans of data were chosen and a straight line has only two unconstrained parameters (i.e., $y = a + bx$), then the least squares fit will be greatly over constrained and the results will be, if anything, conservative. These results are:

4.1 Summary of Accuracy Results

Track No.	S_R (feet)	S_{AZ} (degrees)	Location from Radar
1	167	.06	17 nmi SE
2	144	.10	10 nmi SW
3	0	.04	19 nmi SW
4	121	.19	9 nmi E

average range error = 108 feet
average azimuthal error = $.10^{\circ}$.

These accuracy results compare quite favorably with those obtained on MTD-I.

A test was made running the DABS Experimental Facility at Lincoln Laboratory and the MTD-II system simultaneously. Outputs of both systems are shown in Figure 14. ATCRBS beacon-equipped aircraft were seen by the DABS sensor. The MTD-II system detected the same aircraft as well as those which were not transponder equipped.

The FPS-20/MTD-II system is in the final stages of system integration. It is expected that results will be ready by the time of the AGARD meeting in October 1978.

5. CONCLUSIONS

We have presented a description and initial results of a second-generation Moving Target Detector (MTD) processor. These results indicate that the MTD's automated tracking performance is excellent in any of the clutter environments encountered. Continuing tests of the ASR-7/MTD and FPS-20/MTD will be made in the coming months.

6. ACKNOWLEDGEMENT

Many members of Lincoln Laboratory's Group 43 contributed to the success of this development, among them D. Karp, W. H. Drury, C-S. Lin, D. H. Griffin, M. H. Malone, J. Anderson, N. Barnert, W. Beal, D. Sullivan and R. Burr. We wish to acknowledge the FAA's continuing support of the work described herein. In particular we wish to thank Messrs. K. Coonley and D. Turnbull of ARD-240 for their encouragement and critical review. We also wish to thank Mrs. Linda Wesley and Mrs. Joanne Fitzgerald who prepared this manuscript.

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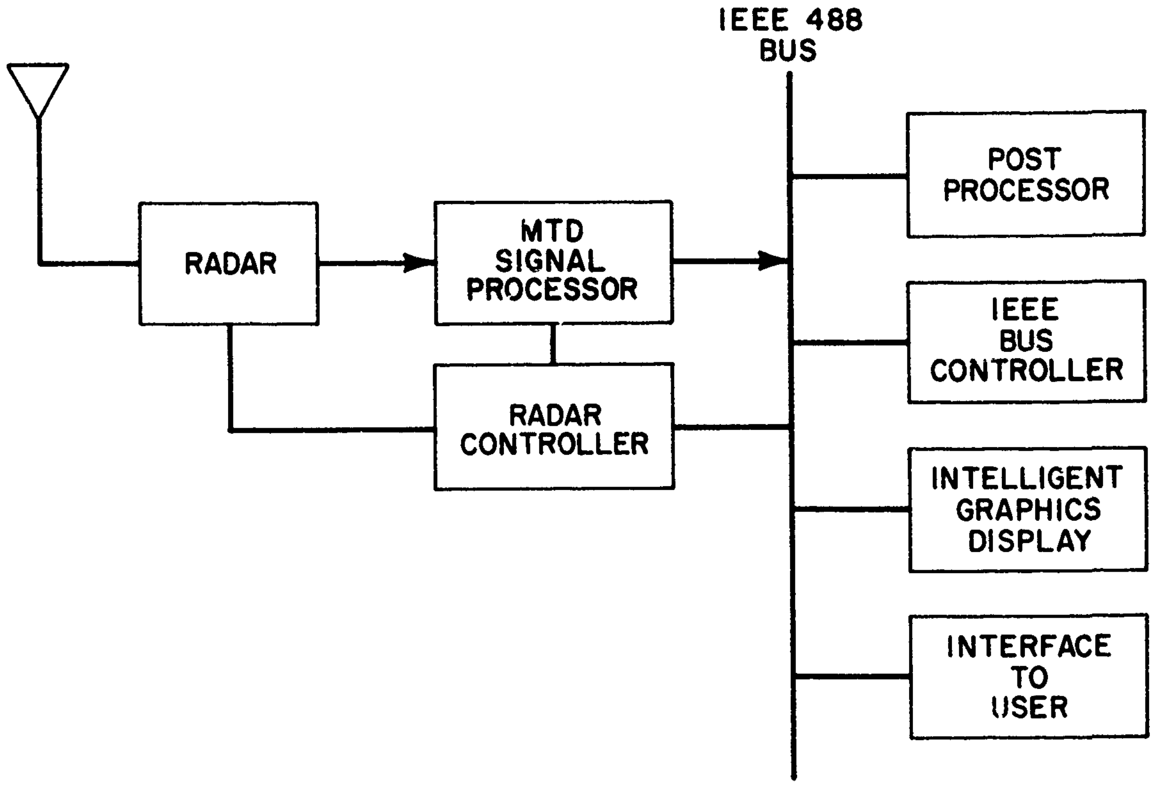

Figure 1 - BLOCK DIAGRAM OF MTD-II RADAR SYSTEM

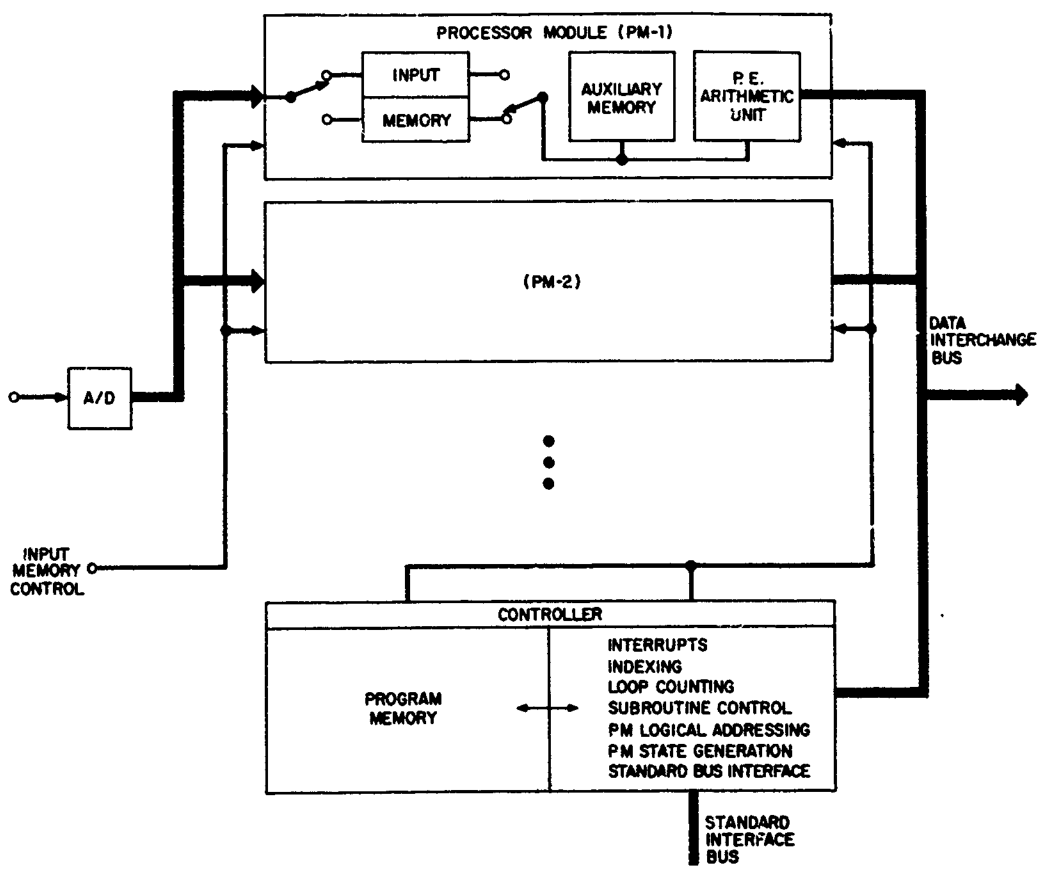

FIGURE 2 - BLOCK DIAGRAM OF PARALLEL MICROPROGRAMMED PROCESSOR (PMP)

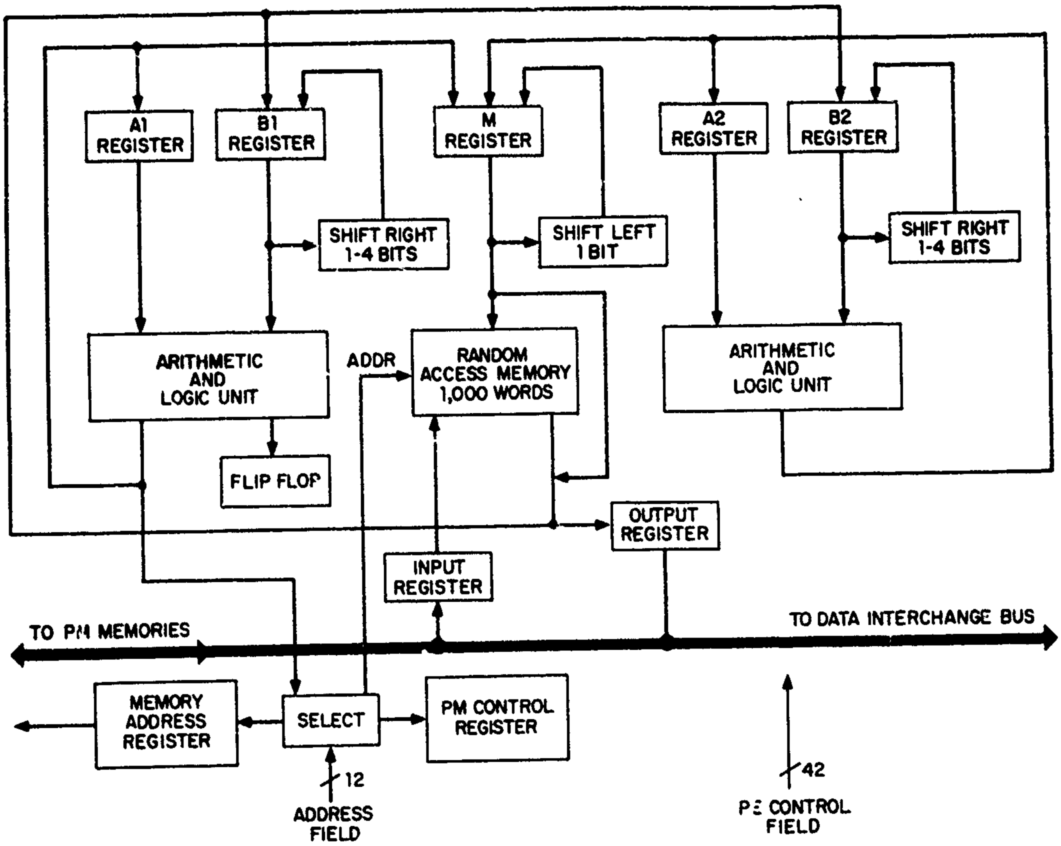

FIGURE 3 - BLOCK DIAGRAM OF PROCESSING ELEMENT (PE)

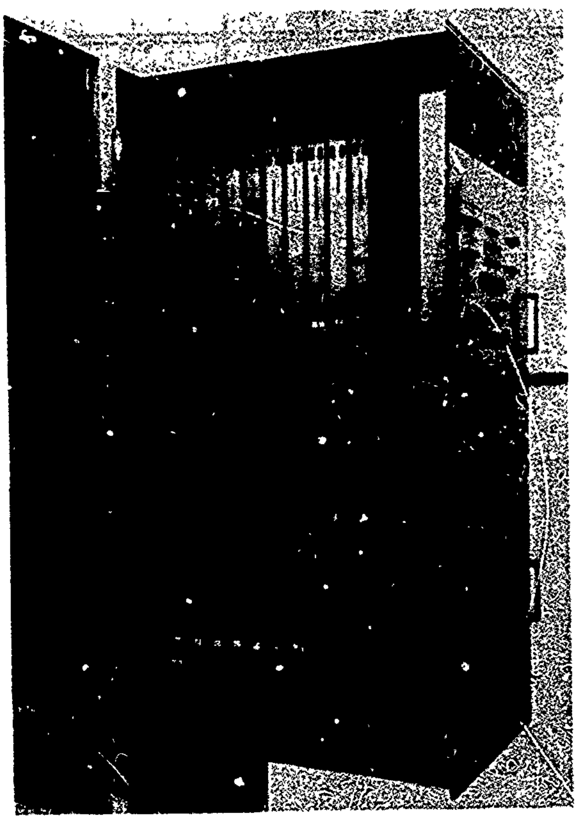

FIGURE 4 - PHOTOGRAPH OF PMP-2

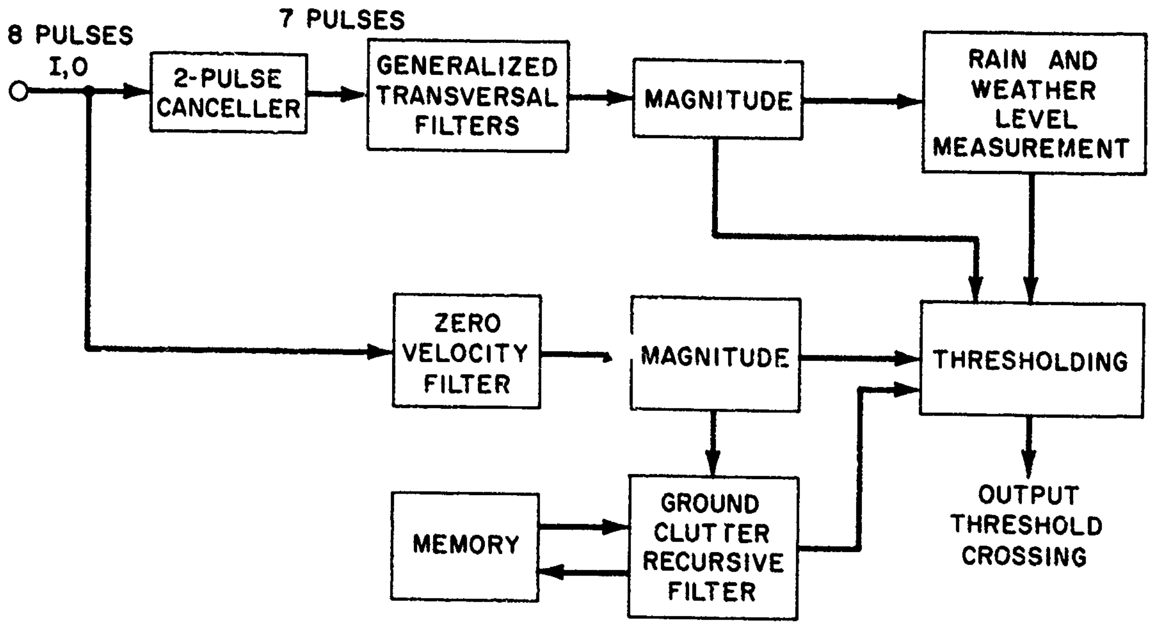

FIGURE 5 - BLOCK DIAGRAM OF MTD-II SIGNAL PROCESSING ALGORITHMS

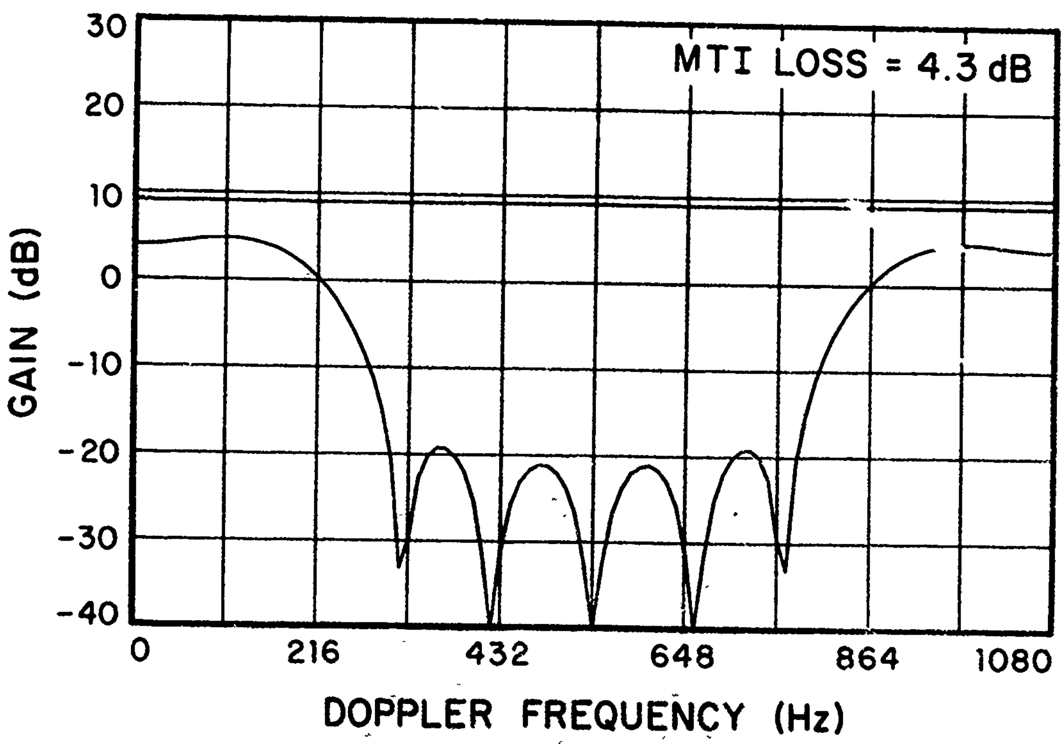

FIGURE 6 - DOPPLER RESPONSE OF ZERO VELOCITY FILTER

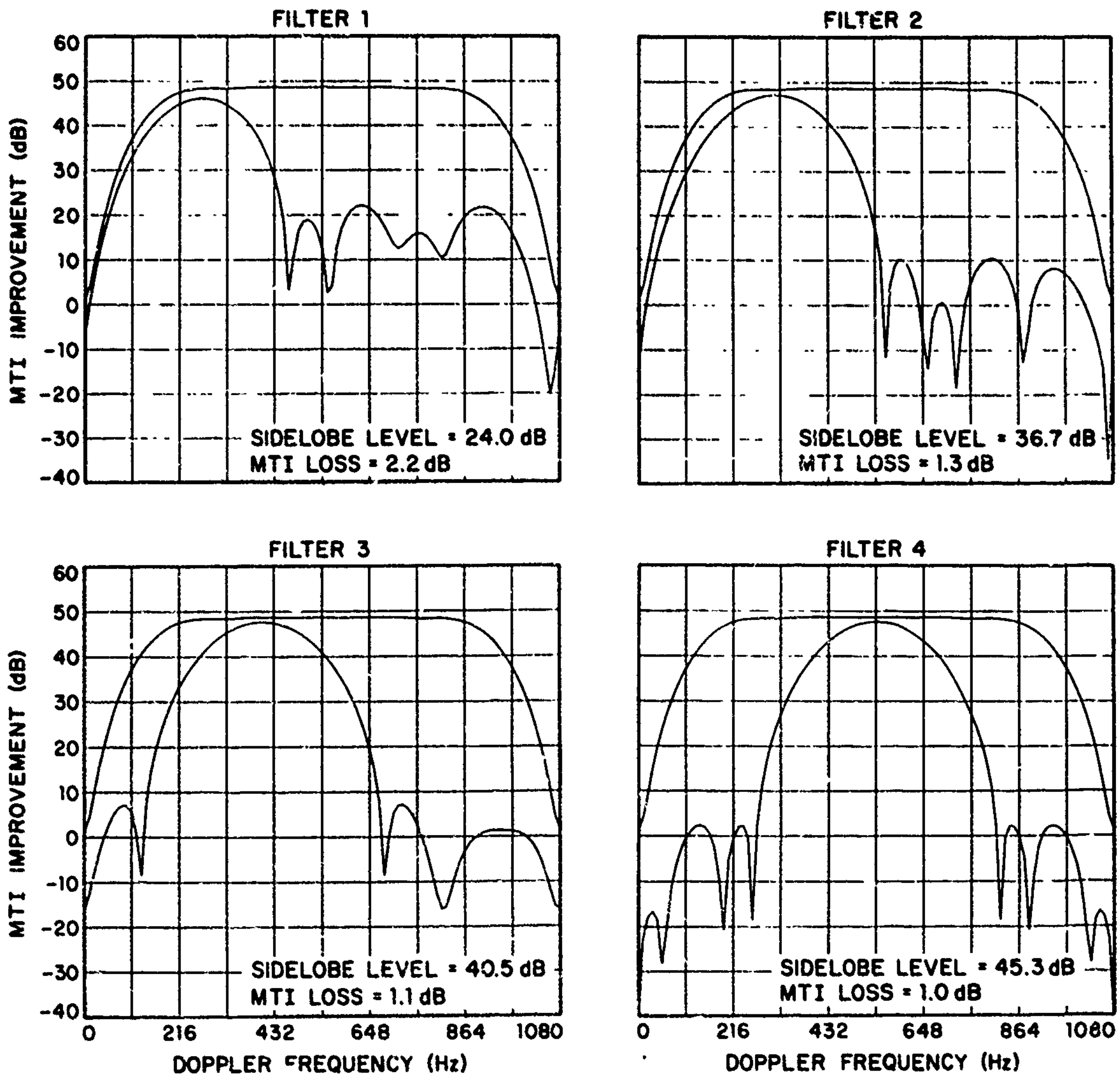

FIGURE 7 - MTI IMPROVEMENT VS DOPPLER FREQUENCY FOR MTD-II DOPPLER FILTERS

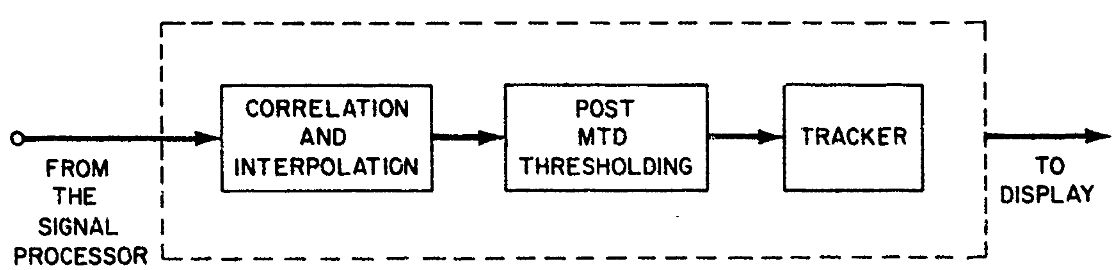

FIGURE 8 - BLOCK DIAGRAM OF POST-PROCESSING ALGORITHMS

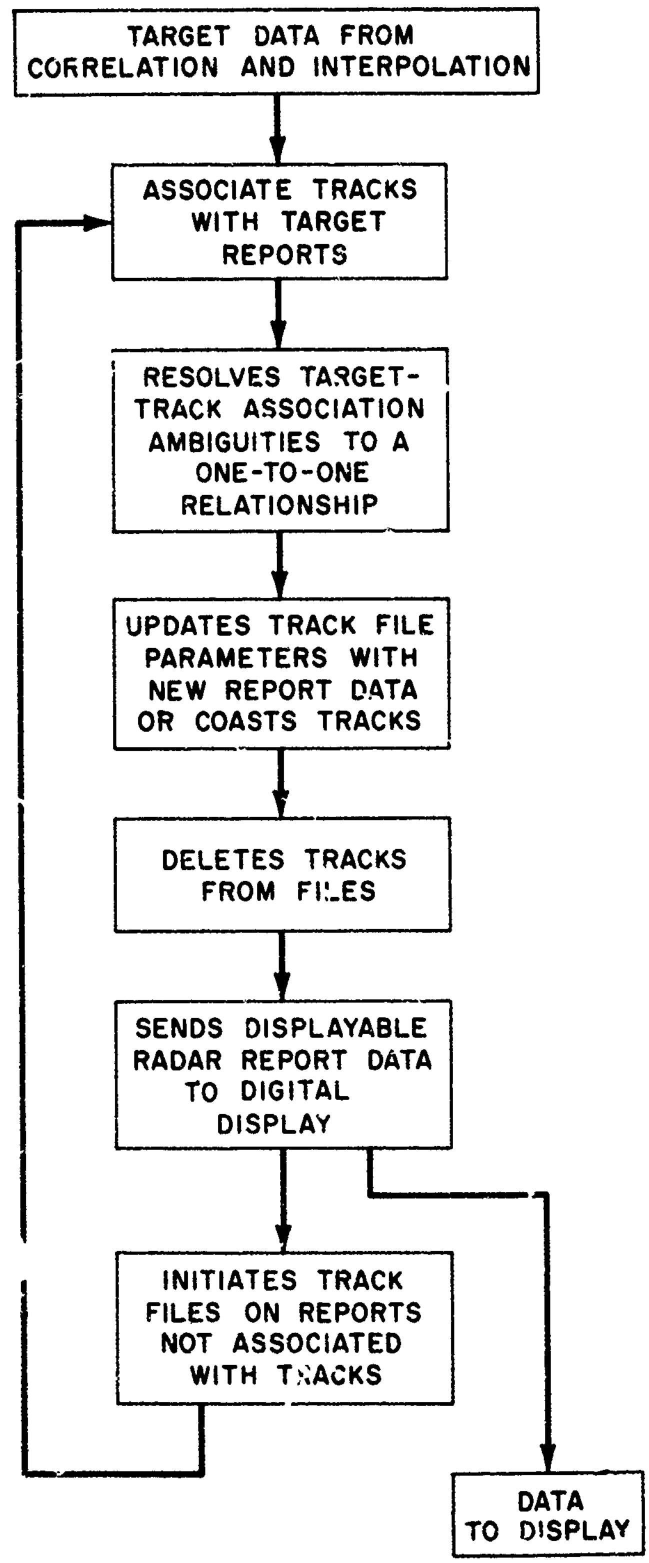

FIGURE 9 - BLOCK DIAGRAM OF SCAN-TO-SCAN CORRELATOR

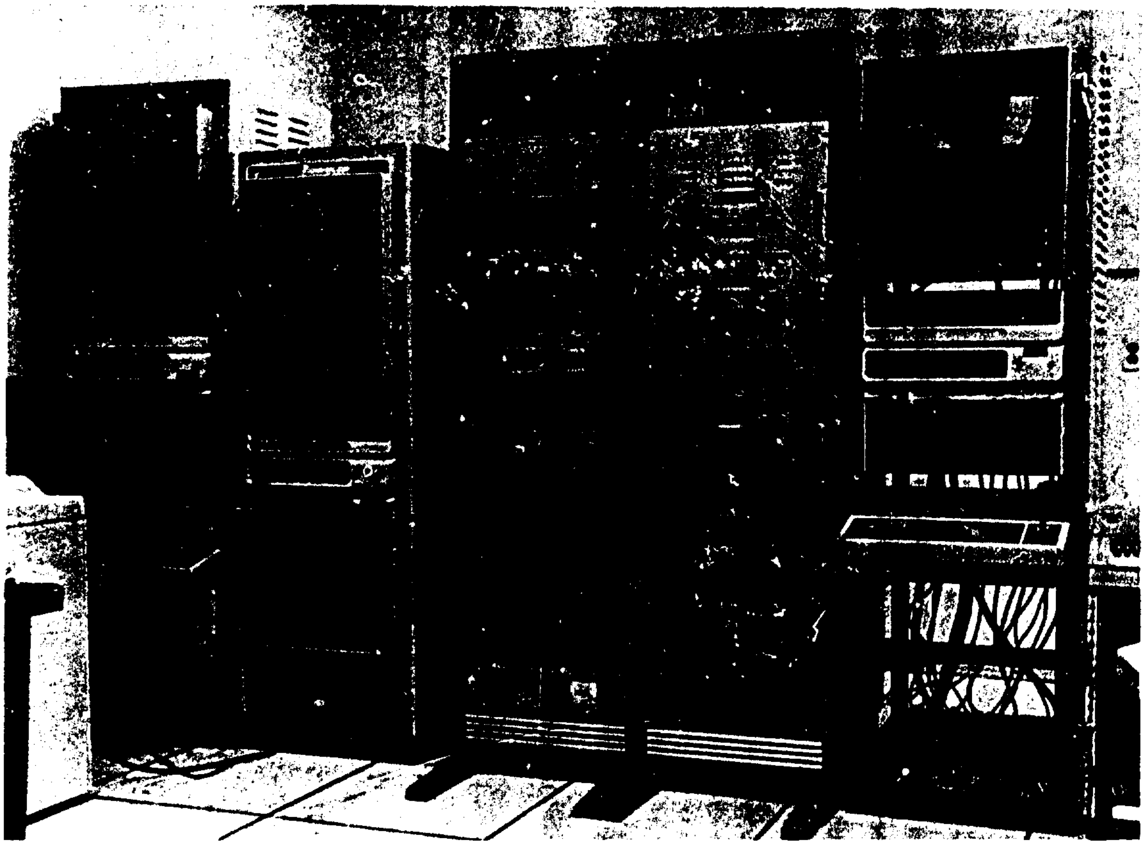

FIGURE 10 - PHOTOGRAPH OF MTD-II SYSTEM

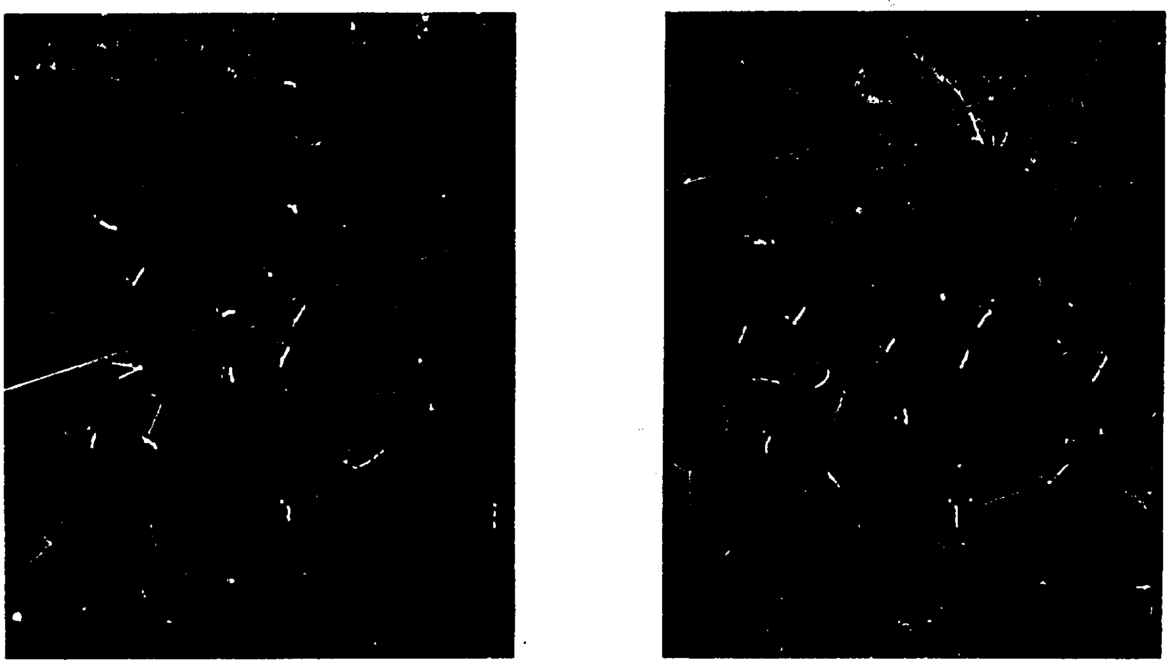

FIGURE 11 - PMP-2 PERFORMANCE IN NORMAL ENVIRONMENT

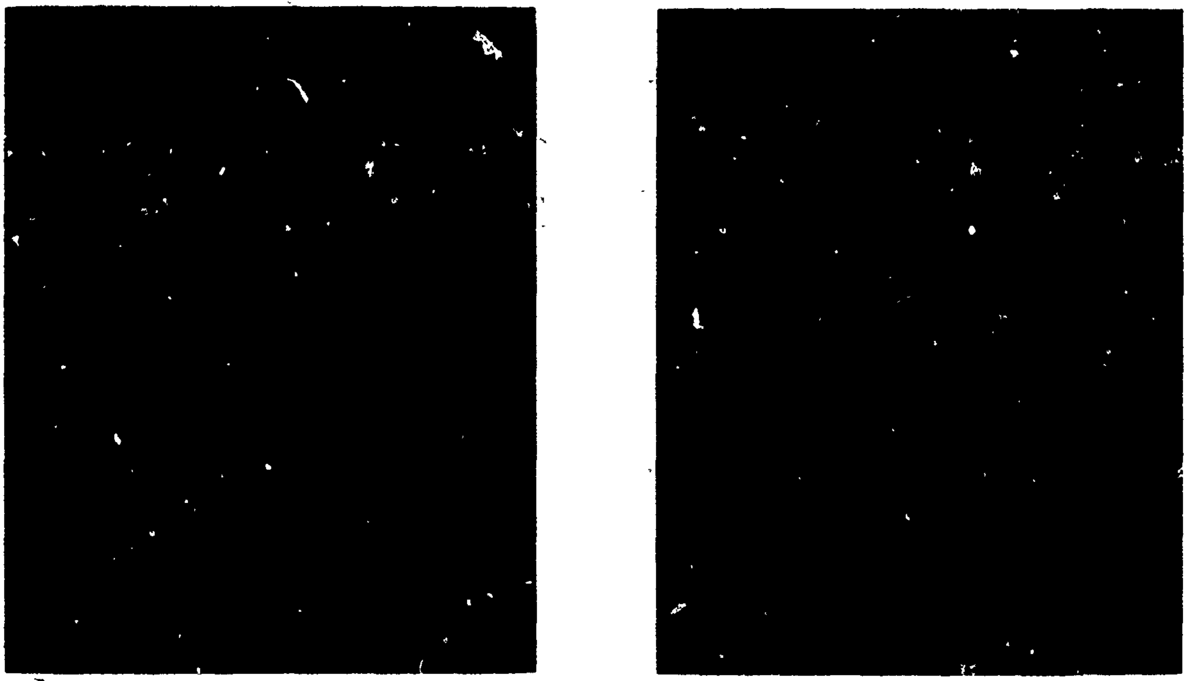

FIGURE 12 - PERFORMANCE IN AUTOMOBILE ENVIRONMENT

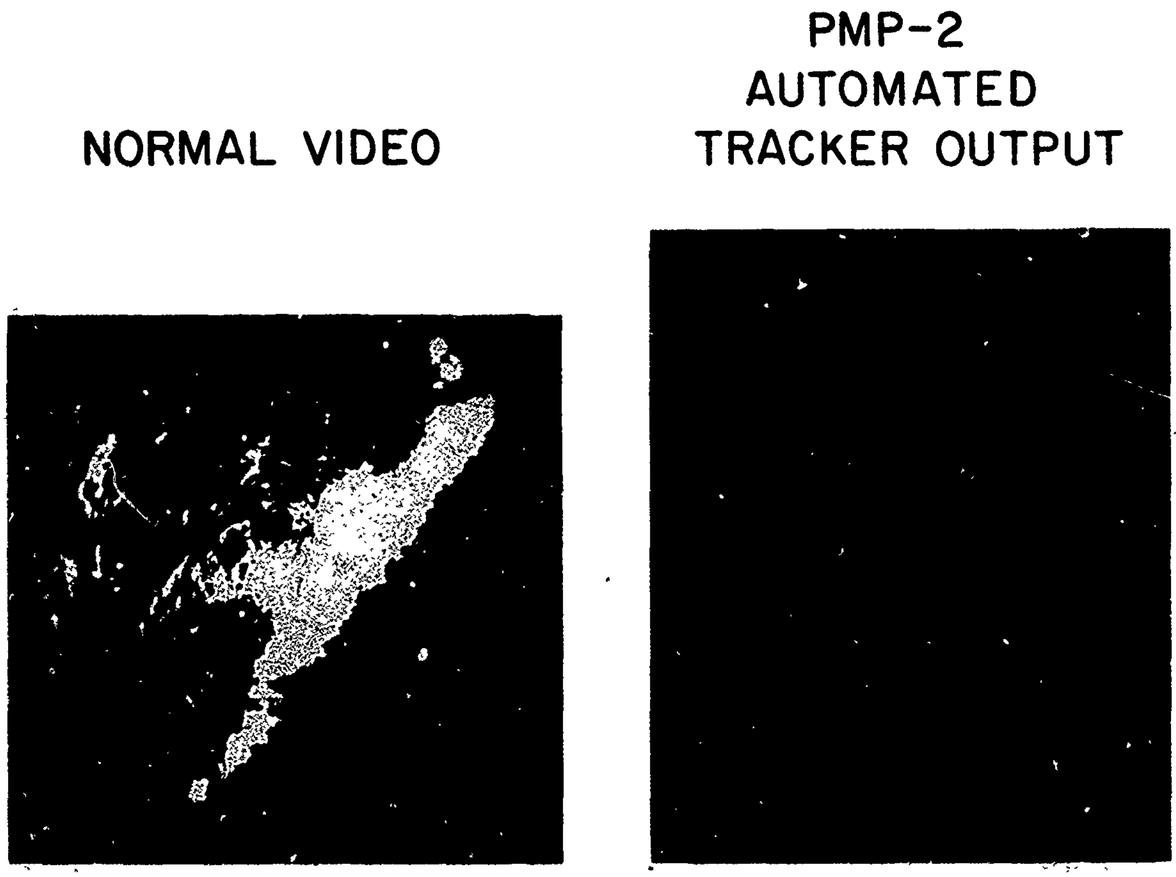

FIGURE 13 - PERFORMANCE IN HEAVY RAIN

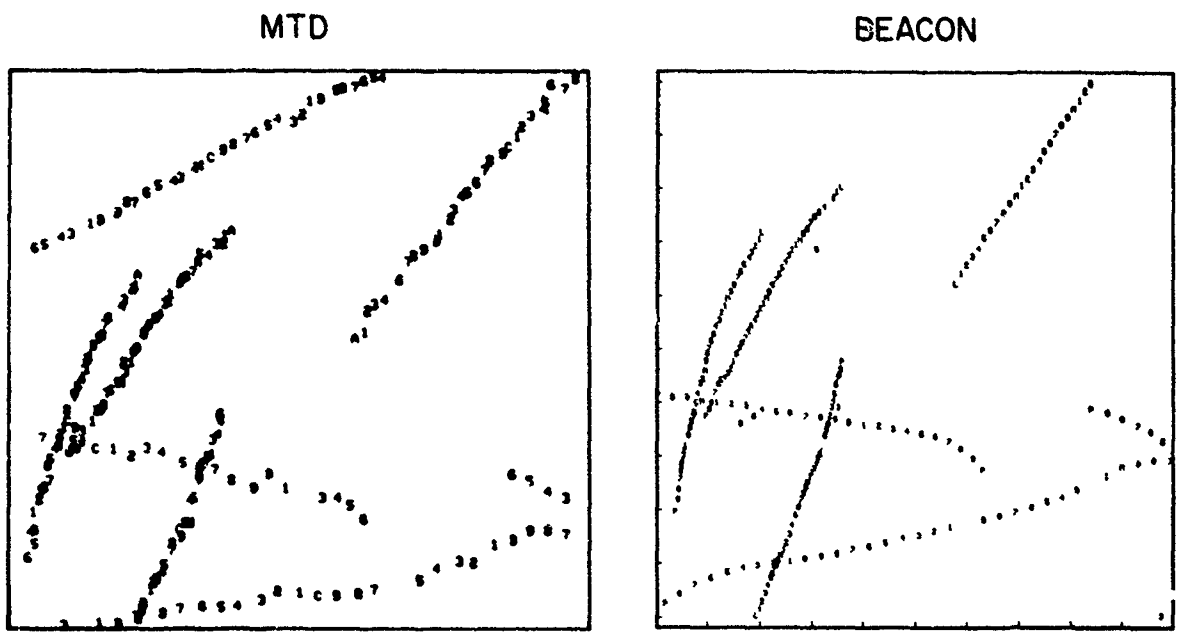

FIGURE 14 - AUTOMATED TRACKER OUTPUT - MTD VS BEACON

DISCUSSION

F.Herzmann, FRG

You have shown us a slide with very heavy rain and a very small aircraft which is tracked by your radar. Do you know if the aircraft was equipped with a beacon?

Author's Reply

The beacon processor was shut off.

E.Brookner, USA

I realize that you still have engineers with their hands on the equipment. Could you tell us what reliability you achieve?

Author's Reply

The least reliable components are the mini computers. The PMP has an MTBF of about one month. (This is excluding the reliability given by the spare PM module.)

E.Brookner, USA

You mentioned that the clutter was 45 dB above the thermal noise for the very severe rain storm. Where is this clutter suppressed relative to noise by the MTD?

Author's Reply

It is suppressed in the signal processor by doppler filtering.

BEAM STEERING AND SIGNAL PROCESSING WITH A PHASED ARRAY RADAR SYSTEM FOR AUTOMATIC TRACK INITIATION

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SUMMARY

The relations between the main system functions search, acquisition, and tracking and their radar counterparts detection, interference reduction and position finding are explained in detail by an experimental radar system named ELRA. For automatic track initiation a lot of radar tasks with different parameters must be handled partly simultaneously and partly sequentially which demands various kinds of data transfer between the radar antennas and the tracking computer.

It is pointed out that spatial distribution of targets and interferences, the radar physics and the tracking process require a variable integration time for optimum signal processing dependent on the target range, direction and estimated cross section and on the information from a clutter map, and how adaptive clutter suppression and jammer cancellation can be included to this with modest reduction of the efficiency. The demand for a high detection probability and location accuracy and limitations in power and time with long-range surveillance systems can be overcome by a multiple-beam concept using interlaced transmit-receive processing.

1. INTRODUCTION

Flexibility and multifunction operation are the main demands on future radar systems in the military area. Objects with very different velocities, reflection characteristics and flight trajectories must be detected, located, classified and tracked, and tasks like defence guidance control should be additionally handled by the same radar system.

The use of an array antenna with electronically-steered phase shifters combined with a system of special and general-purpose computers allows a system to be set up which satisfies these demands. But these antennas are more expensive than conventional mechanically-steered ones. The employment of these radar units is efficient only if greater versatility is utilized by an adequate expense in signal processing and data handling in multifunction operation.

The experimental system ELRA under construction shall be used to find the limits of versatility for those electronically-steered radar systems. In the final stage the maximum range will be about 200 km for this S-band system which will permit the study of areas such as multifunction operation, target tracking and system overload by a great number of daily present aircrafts in realistic conditions.

The transmitting antenna and the receiving antenna are build up in separate cabins (Fig. 1). Both are active antennas with a thinned random distribution of the elements. This enables a stepwise construction of the whole system with reduced problems of mutual coupling, element tolerances and system breakdown. A very fast special computing unit is used for the steering of the phase shifters which additionally allows the monitoring and the correction of each antenna module separately (Hüschelrath, G., 1976). With those active array antennas, special beam forming for sidelobe reduction and multiple-beam generation for position finding and target resolution and for the search with a cluster of beams without reduction of the signal-to-noise ratio is possible.

2. DISTRIBUTION OF THE ENERGY

The main radar tasks in a multifunction system are:

(1) Detection of new targets or decision for a target.

(2) Determination of the target position with suppression of neighbouring targets or decision for multiple targets.

(3) Estimation of target parameters like echo power, doppler frequency and fluctuation for an improved target decision and classification.

(4) Suppression of interferences, clutter and jammers, including interference detection, parameter estimation and registration.

This multifunction operation demands different kinds of energy management if a maximum amount of information from all targets in different interferences should be obtained with minimum energy per cell. That means a high degree of complexity and flexibility in the overall signal and data processing. Neither the way nor the parameters should be chosen fixed, but matched to each a-priori knowledge on targets and disturbances.

Generally the energy can be varied in three dimensions: transmitted power, antenna gain or beamwidth and time. Power and antenna gain are the most cost-consuming factors in array antennas. Time management is, therefore, that degree of freedom which can be handled with least amount of hardware and control.

Additionally the trend in radar systems with array antennas leads to the employment of semiconductor devices in active antenna modules to improve the meantime between breakdown. Inherent to that is a reduction of the peak-to-mean power ratio which also demands the use of pulse modulation or time-division multiplex processing.

The time management can be handled in two ways:

(1) Variation of the transmitted pulse length combined with pulse modulation for target resolution. This demands little control since only one pulse is transmitted. For reasons of range ambiguity only few codes can be used.

(2) Variation of the number of pulses, the echoes of which should be coherently integrated. This way includes the possibility of clutter suppression by doppler filtering and enables the achievement of a fixed effective signal-to-noise ratio necessary for all targets in search and position finding to get a definite detection probability at a prescribed false-alarm rate and a definite position accuracy if the beamwidth, the pulse length, the transmit energy and the antenna gain are kept constant (Hanle, E., 1975).

That means an adaptation of the number of pulses during position finding to the known target range and direction corresponding to the scan-angle dependent antenna gain, to the estimated single-pulse signal-to-noise ratio and to the doppler processing necessary for clutter suppression. During search the number of pulses can be matched to the spatial distribution of expected targets and disturbances or to other threat criteria. Sequential detection (Wirth, W.D., 1975) and ranking algorithms (Dannemann, H., 1972) can be additionally employed. This matching of the number of pulses to a-priori information yields a gain in power or time of up to 10 dB referred to fixed-sample-size techniques.

3. RADAR FUNCTIONS IN THE ELRA SYSTEM

In the ELRA system up to now, two different main radar tasks are realized:

(1) Detection with transmit pulses of 10 µs and incoherent integration for search in areas without clutter.

(2) Position finding with transmit pulses of 2 µs, coherent integration, doppler filtering, monopulse angle measurement (Sander, W., 1973) and range interpolation

a. for tracking purposes
b. for acquisition following a successful incoherent search
c. for search in clutter areas.

The choice of the suitable transmit pulse and signal processing during search is controlled by a clutter-area map (Fig. 2). At low elevation for near targets coherent integration is combined with range-limited ground-clutter prefiltering by a recursive step-scan MTI. At high elevation and low ranges the incoherent sequential search is used which can be also combined with the recursive prefilter for sidelobe clutter reduction. Rain clouds or chaff can be reduced by coherent processing with adaptive doppler filtering (Klemm, R., 1978). The employment of the prefilter for tracking is also controlled by the adaptive fine-grained map of the clutter areas.

The ELRA-system will be provided with some additional tasks:

clutter map generation	combined with search in noise
clutter parameter estimation clutter suppression (MTI and adaptive doppler filtering)	combined with position finding and search in clutter
target parameter estimation target classification neighbouring target resolution	combined with position finding
jammer suppression (adaptive spatial filtering)	combined with beam forming
jammer direction finding (passive mode) target identification (secondary radar) target guidance (illumination, data transmission)	not planned so far

Theoretical investigations to the areas of classification and jammer suppression have been published (von Schlachta, K., 1975 and Klemm, R., 1975).

4. BEAM MULTIPLEX OPERATION

The transmission of many pulses in each direction for signal-to-noise improvement and clutter suppression leads to a long search time and to the occurrence of delay times during the treatment of track commands which cannot be tolerated.

This constraints are overcome in the ELRA system by time-division multiplex operation. That means, by overlapping of transmit-receive periods, multiple beams looking in different directions can be handled as if they were present simultaneously. In position finding for tracking of known targets, the deadtimes between pulse transmission and echo reception can be utilized. During search processing the reception of echoes from different directions is possible if longer transmit pulses are

used. The reduced range resolution and clutter suppression inherent to these longer pulses can be tolerated if each detection is followed by an acquisition step which additionally allows an increased false-alarm probability in the first step.

The buffers and control units are layed out for an interleaved processing of up to six beams. Therefore the simultaneous search in six directions for targets at the same range is possible if only one direction demands coherent processing, or the position finding of up to six targets at different ranges or some mixtures of both (Fig. 3). For reasons of data transfer and cost efficiency in this multiplex processing, up to now fixed radar intervals of 2 ms are used. The transmit pulses must be grouped before reception, since the transmit-receive signal-to-noise ratio exceeds the side-lobe attenuation. The time before transmission can be used for threshold normalization or sidelobe adaptation to interferences.

Fig. 3 additionally shows the data transfer in successive radar intervals. After transmission of the steering commands for up to 6 radar tasks, the phase values are computed by a special unit for all transmit and receive elements according to their location on the antenna plane from the demanded direction coordinates. During the following interval the real radar operation takes place. At the beginning of the third interval the results are available. By pipeline processing radar operation is possible in each interval.

Basically the up to six beams could be varied from interval to interval. For reasons of storage, handling and control during integration and doppler filtering the same beam is used for one radar task in succeeding intervals. Fig. 4 shows an example of the multiplex operation with different dwell times and various range gates according to the expected targets for several, to a certain extent, parallel-handled radar tasks using a mixture of serial reception for position finding and time-division multiplex reception for search. The number of pulses can be chosen for each beam separately but is limited to 64 to prevent long delay times during position finding for tracking purposes and to guarantee that the target has not changed its position essentially during the integration time.

5. RADAR CONTROL AND DATA DISTRIBUTION BY A PROCESS COMPUTER

On the way from the radar antenna to the control display the data rate must be reduced from about 100 bit/µs to about 100 bit/s. The flexibility in processing must be increased conversely to make the best of the possible degrees of freedom.

This demands the employment of processing units of different kinds, from very fast simultaneously-working processors with fixed parameters at the antennas and for signal processing to general-purpose computers for data processing, for tracking and display purposes and for the system control. A limited flexibility can be inserted with the fast special processors by adaptive signal processing, e.g. by storing different sets of filter functions. On the other hand the processing rate in the general-purpose units can be increased by parallel-working multiprocessors. In each case the use of one type of processing unit for the whole area of signal and data processing in a multifunction radar system is not possible.

For reasons of cost efficiency a process computer is used in the ELRA system as an additional processing step between the special units for signal processing at the antennas and the central tracking computer (Fig. 5). Different jobs must be handled by this process computer:

(1) handling and scheduling of different radar tasks,

(2) multifunction control by parameter setting for signal processing like length of the transmit pulse, reception bandwidth, decision thresholds, doppler filtering and range gate,

(3) energy management by matching the number of pulses to the target distance and direction, to the target parameters if known, to different kinds of interferences and to the requirements in detection probability and position finding accuracy,

(4) control of the multibeam time-division multiplex operation,

(5) generation and scanning a list of search directions.

A general-purpose computer at this place additionally offers the possibility for the control and monitoring of the antennas and the signal processing units in deadtimes without radar tasks, for a graceful degradation of the radar processing in overload times by priority control and for a stepwise and expansible build up of a radar system which is also suited for future requirements.

6. RADAR TASK HANDLING

The search for new targets and the position finding of known targets for tracking purposes is ordered from the central computer by commands to the process computer including information upon the search volume or correlation gate, on the desired detection and false-alarm probability and on estimated parameters on the target and its environment (van Keuk, G., 1978).

Fig. 6 shows the succession of these main tasks. During search, all directions in the demanded area are scanned by the process computer on the basis of a list which is ordered by a number or which is transfered from the central computer in advance. Special tactics for a fast and economic search will be used at high elevation and at long ranges by favouring directions with a high probability of targets by a ranking process and by matching the integration time for each direction separately to the local signal-to-noise ratio with sequential detection. In case of detection the process computer initiates a position-finding task immediately subsequent in the same direction with a limited range gate for validation and acquisition to the demands of the tracking process with regard to position accuracy.

. -lutter areas the search scanning is directly combined with the position-finding process in a large range gate, including

doppler processing with fixed or clutter-adaptive filtering using a preselected number of transmitted pulses. In directions with clutter echoes from a limited range area both kinds of search will be performed. The border in range for this different processing is drawn from a clutter-area map which is adapted to variations in the clutter situation by measurements. For track evaluation the position of each target must be measured in predicted areas in space and time ordered by the tracking computer. Each command from the tracking computer initiates a position-finding task in the process computer, generating several transmit pulses, the number of which depends upon the target distance and direction and upon the target and clutter parameters previously estimated.

7. PRIORITY CONTROL

For the multiplex handling up to six radar tasks are accumulated in the process computer and jointly transferred via a data-exchange unit to the different antenna and signal processing units at the beginning of a radar interval. The same radar orders are repeated in each successive interval during the echo-integration time to obtain a complete supervision on the whole radar signal processing by the computer. The radar results from search or position finding are retransferred at the end of the integration process via the process computer to the central computer. Each result can contain the positions and parameters like doppler frequency and signal-to-noise ratio from up to three resolvable targets from different range elements and directions within the beamwidth.

Generally, the process computer has to arrange all present radar tasks corresponding to their importance to the available number of multiple beams and to some physical limitations. The main priority order is:

(1) treatment of running tasks
(2) position finding
(3) search
(4) monitoring.

By this choice no results from presently-unknown targets are generated in overload times. That leads to some kind of graceful degradation automatically which is of great importance in such a complex radar system.

8. SEARCH VOLUME

The antenna gain decreases and the element coupling increases with the scan angle. For that reason the maximum scan angle with one phased-array plane is usually limited to about 60°. The antennas in the ELRA system are therefore tilted to 30°.

With these antennas, searching along a line of fixed elevation, e.g. along the horizon, calls for steering the antenna scan direction along an elliptic curve. Fig. 7 shows the search pattern of the ELRA system for different search volumes. The distances between the steering directions were chosen in a triangular latice after optimization studies (Hanle, E., 1977) to one antenna beamwidth, i.e. to 1.8° in azimuth and elevation for the broadside direction, and are therefore constant in the plane of the direction cosines. The search area is limited by the horizon and by an elliptic line as an approximation to the limit at which the scan loss caused by the antenna element pattern is 6 dB.

The total volume includes about 2000 scan directions from ±60° in azimuth and 0° to 90° in elevation. The maximum slant range is limited to about 200 km by the fixed radar interval. It can be reduced corresponding to a maximum height of 20 km or increased by combining several intervals, e.g. for tracking of satellites. A standard search limited to 6° in elevation is used for targets which enter the control area at maximum range, a horizon search for low flying targets and a lateral search for targets coming from the flanks. Further search lists can be generated, e.g. a spiral search around a given direction where a target was lost or a new target is expected.

The list of the search directions is available in the process computer and can be ordered by the central computer entirely or partly. Special areas, e.g. the horizon, can be scanned more frequently than the rest. A list instead of an algorithm additionally offers essential advantages for the direction-dependent control of different parameters, e.g. for the compensation of the varying antenna gain and for the clutter suppression according to a map. Generally an arbitrary order of the scan directions can be chosen. For the presentation of echoes in a conventional way on a sector PPI successive scanning along lines of constant elevation should be preferred. By way of contrast a random sequence is favourable to radiate minimum scan information and to prevent synchronous interferences in adjacent radar sides.

9. CONCLUSIONS

The control of the antennas and signal processing units by a process computer additionally offers the possibility of storing different radar results for off-line analysis, like echo signals, plots from targets and clutter, test results and maintenance information. During a search along the horizon the clutter plots shown in Fig. 8 were recorded in good correlation to the geographical reality. Later on such data will be the input for the adaptive clutter-area map. Fig. 9 shows some search and tracking plots ordered from the central computer during a helicopter test flight at low level transversing these clutter areas. One can see that the clutter was adequately suppressed by doppler filtering and by the tracking process.

Solely the complete set-up of an experimental system like ELRA with antennas, signal-processing units and data-processing computers enables systematic studies of the operation characteristics and the limits of electronically-steered radar systems. The paper showed how a high degree of complexity and flexibility in antennas and signal processing can be efficiently handled by a special computer for radar control.

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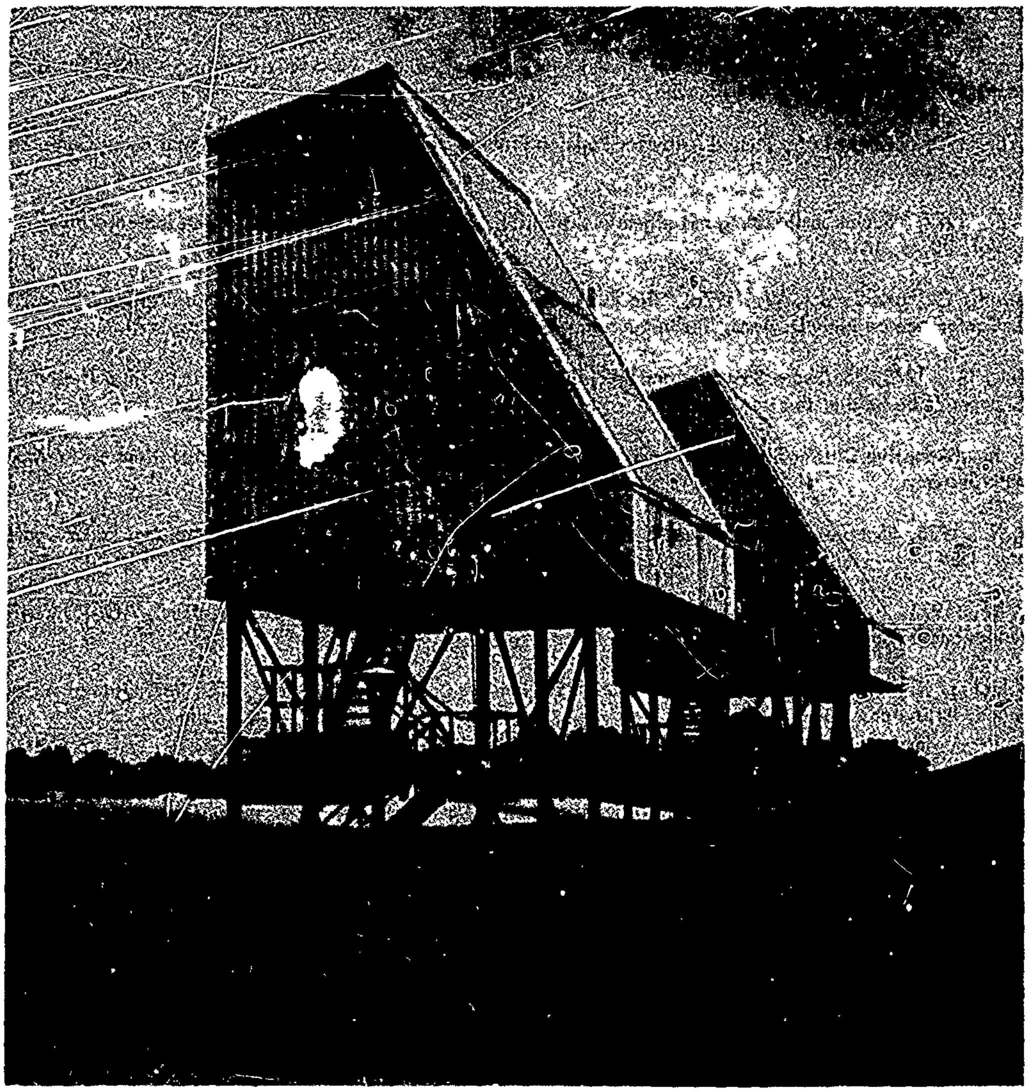


Fig. 1 ELRA Antennas

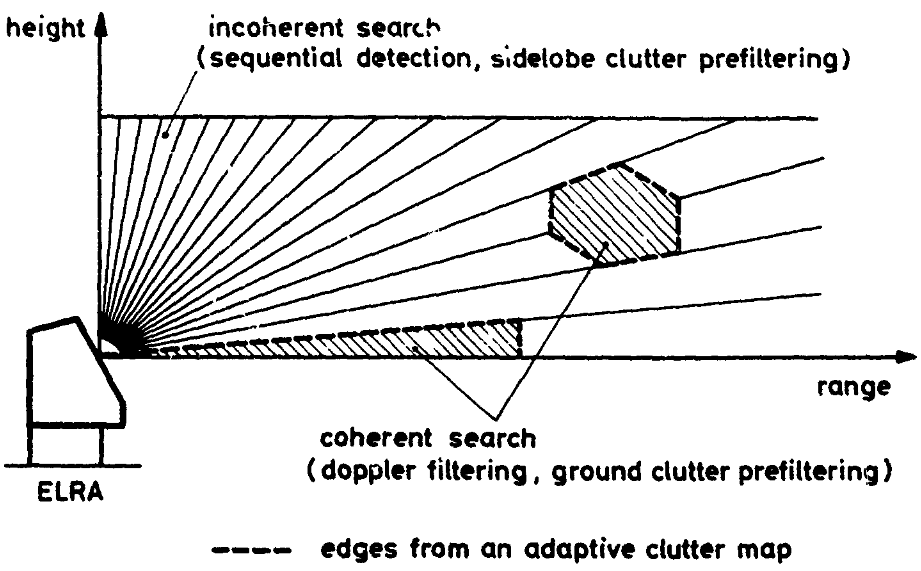


Fig. 2 Search Processing

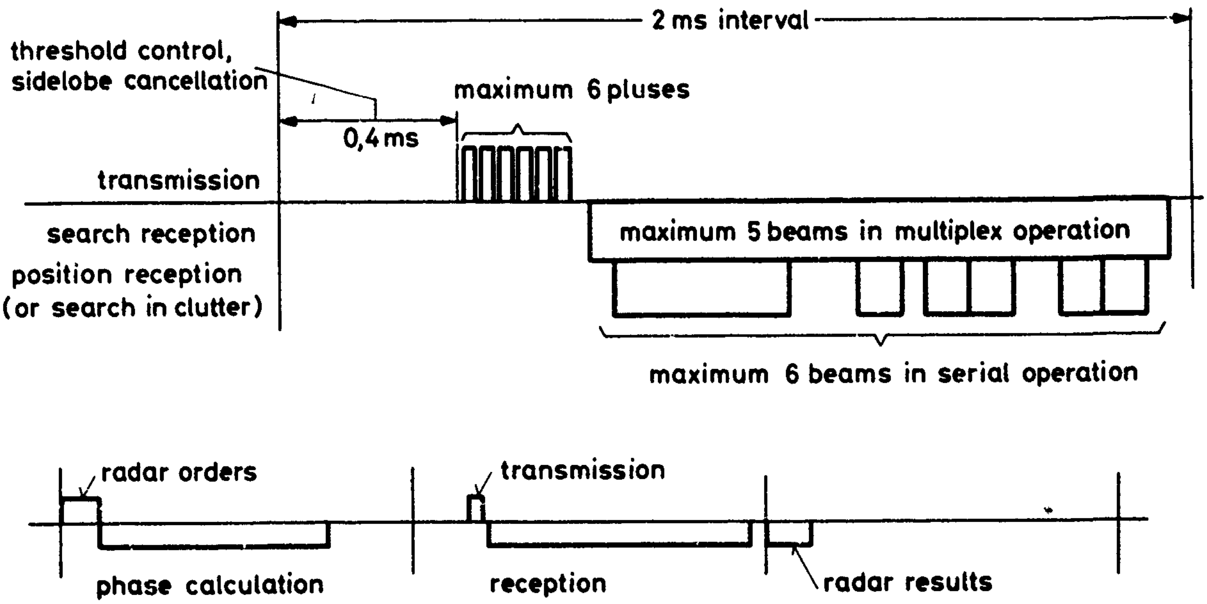
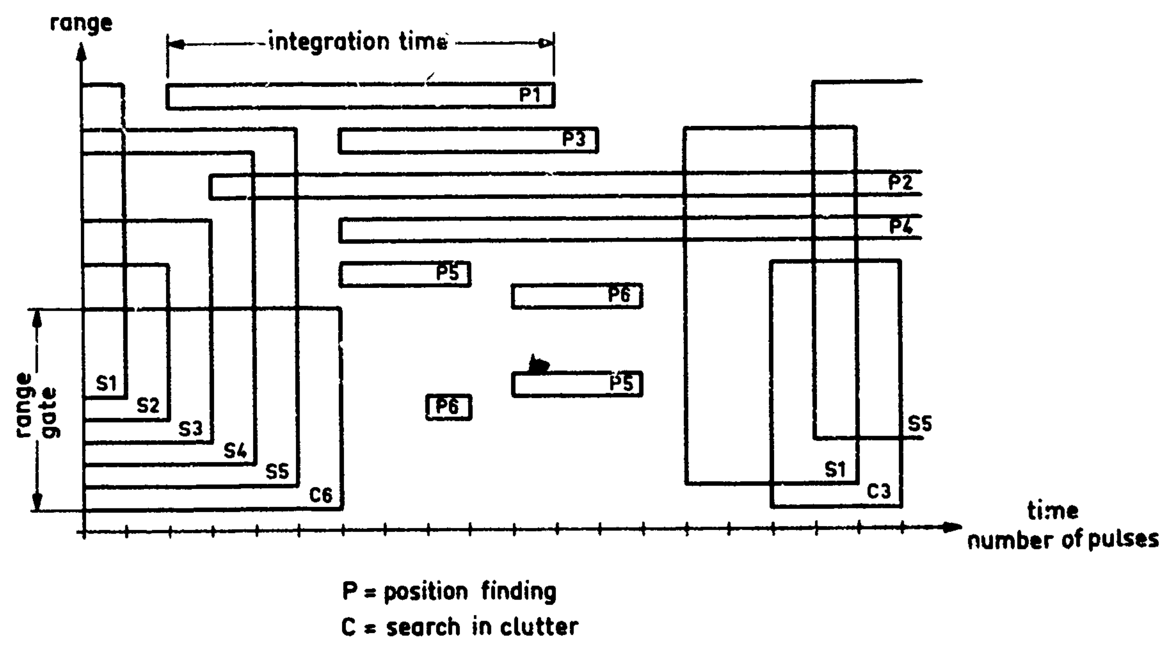


Fig. 3 Time-Division Multiplex Operation for 6 Beams



P = position finding
C = search in clutter
S = search in noise
1.... 6 = number of the beam

Fig. 4 Example of the Beam-Multiplex Operation

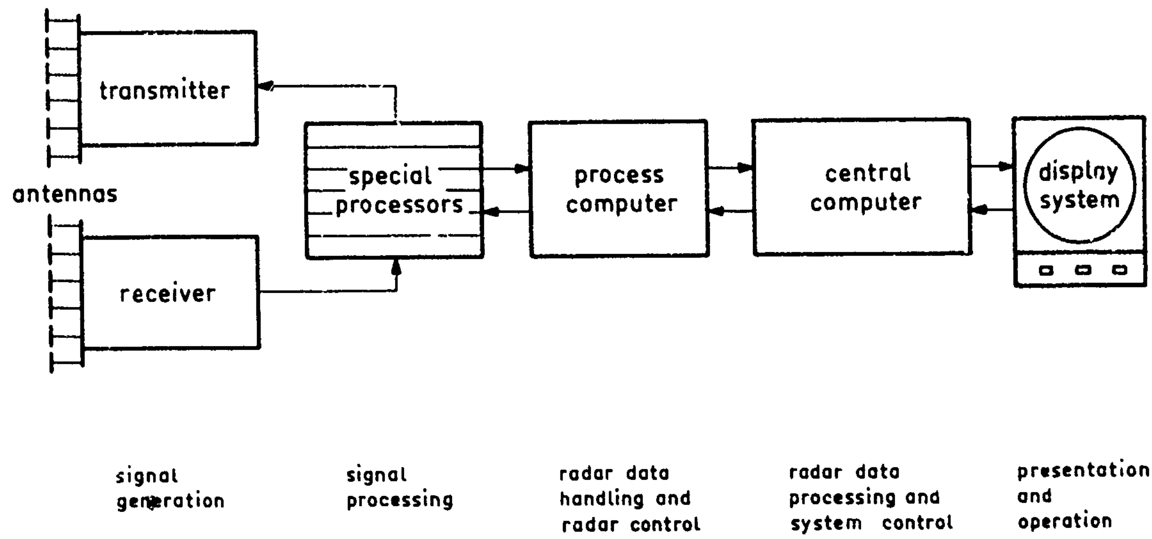


Fig. 5 The ELRA System

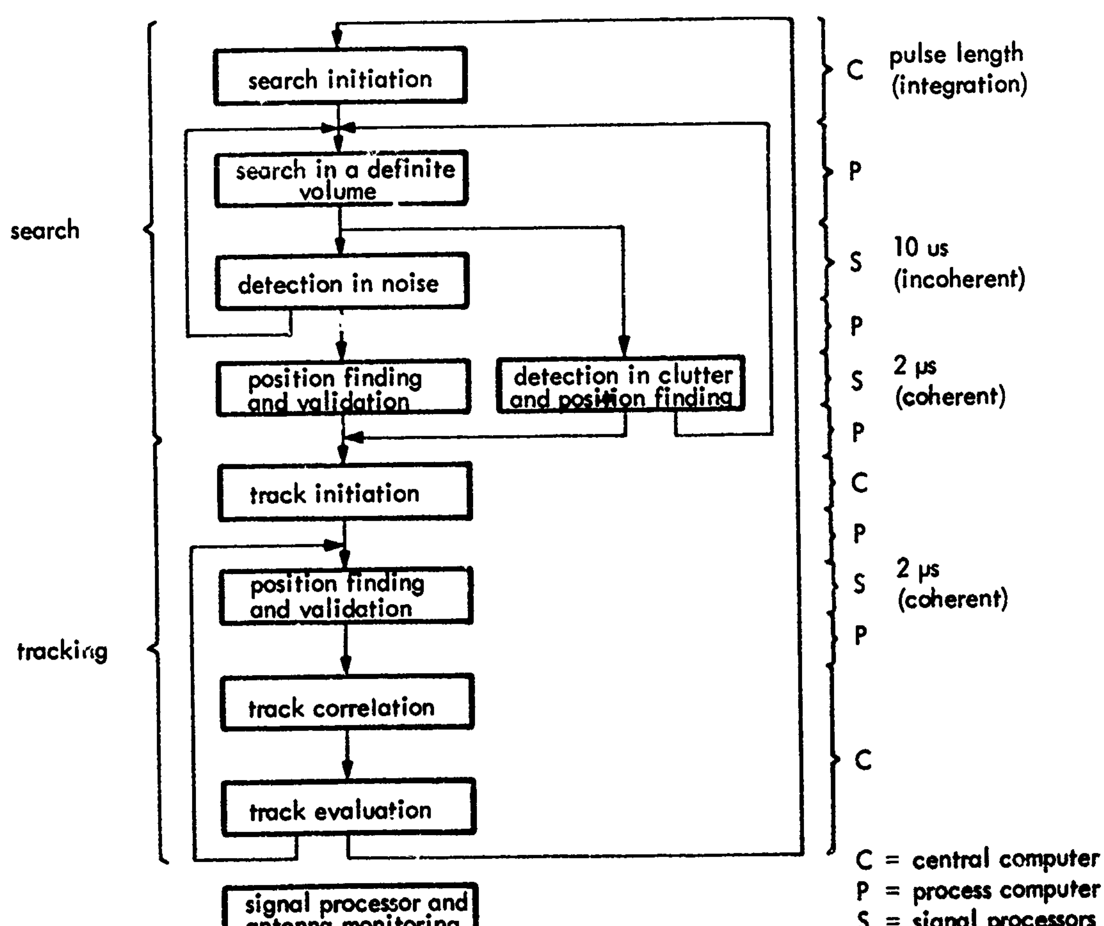


Fig. 6 Main Tasks in the ELRA System

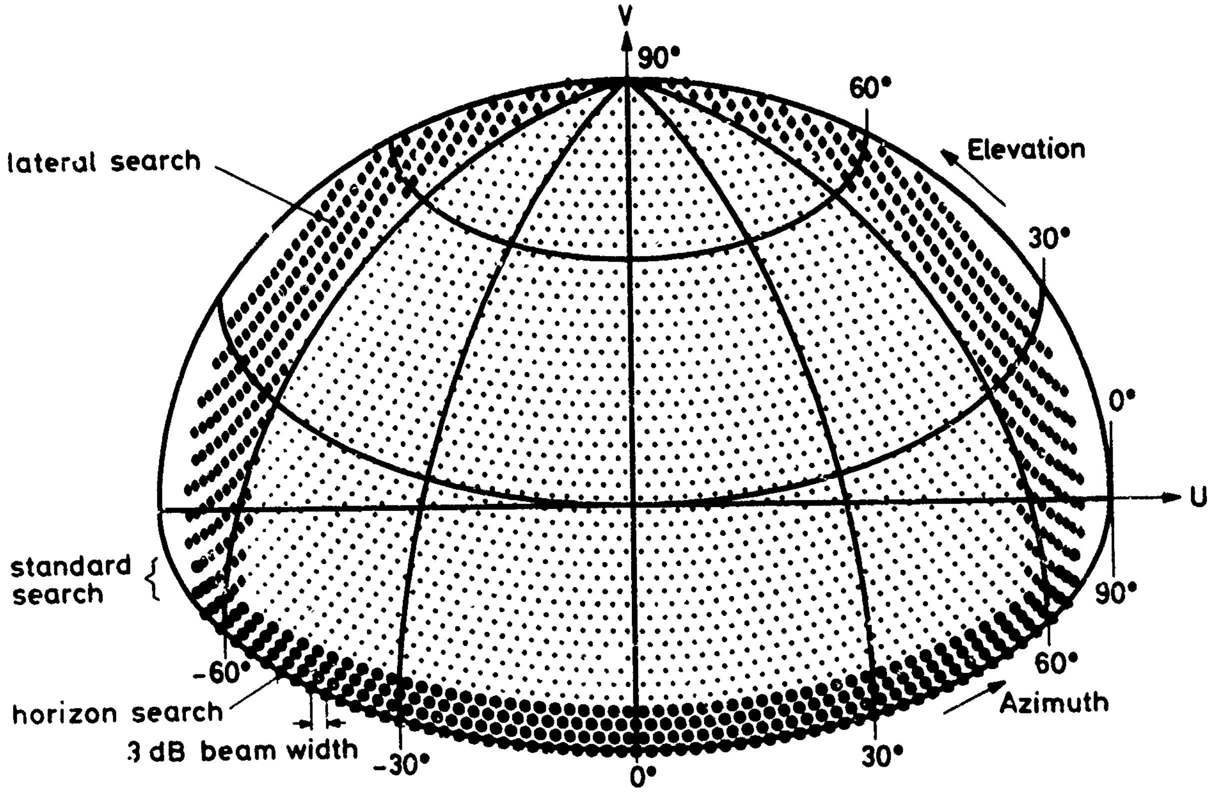


Fig. 7 Search Pattern for a 30° Tilted Antenna

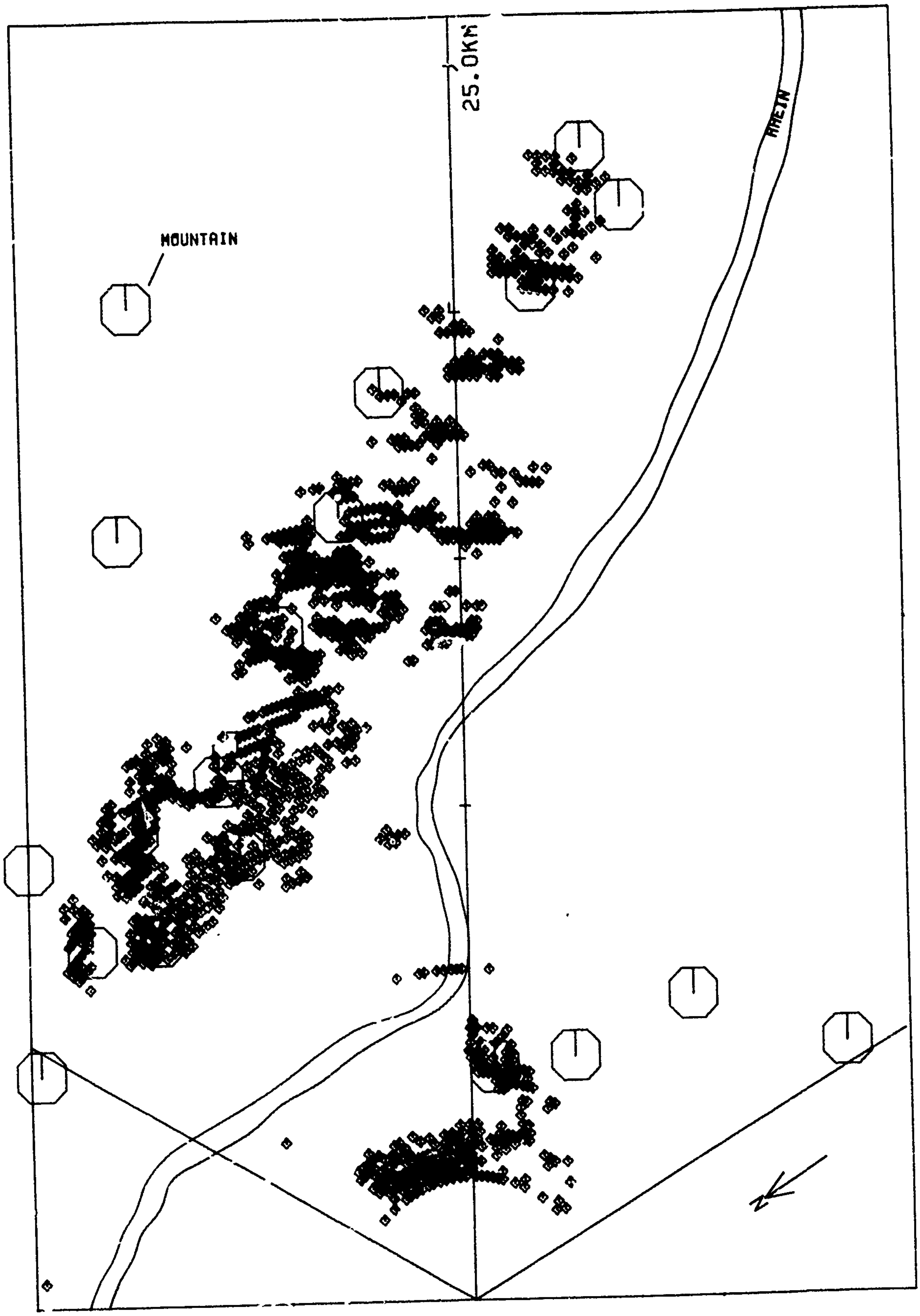


Fig. 8 Clutter Echoes

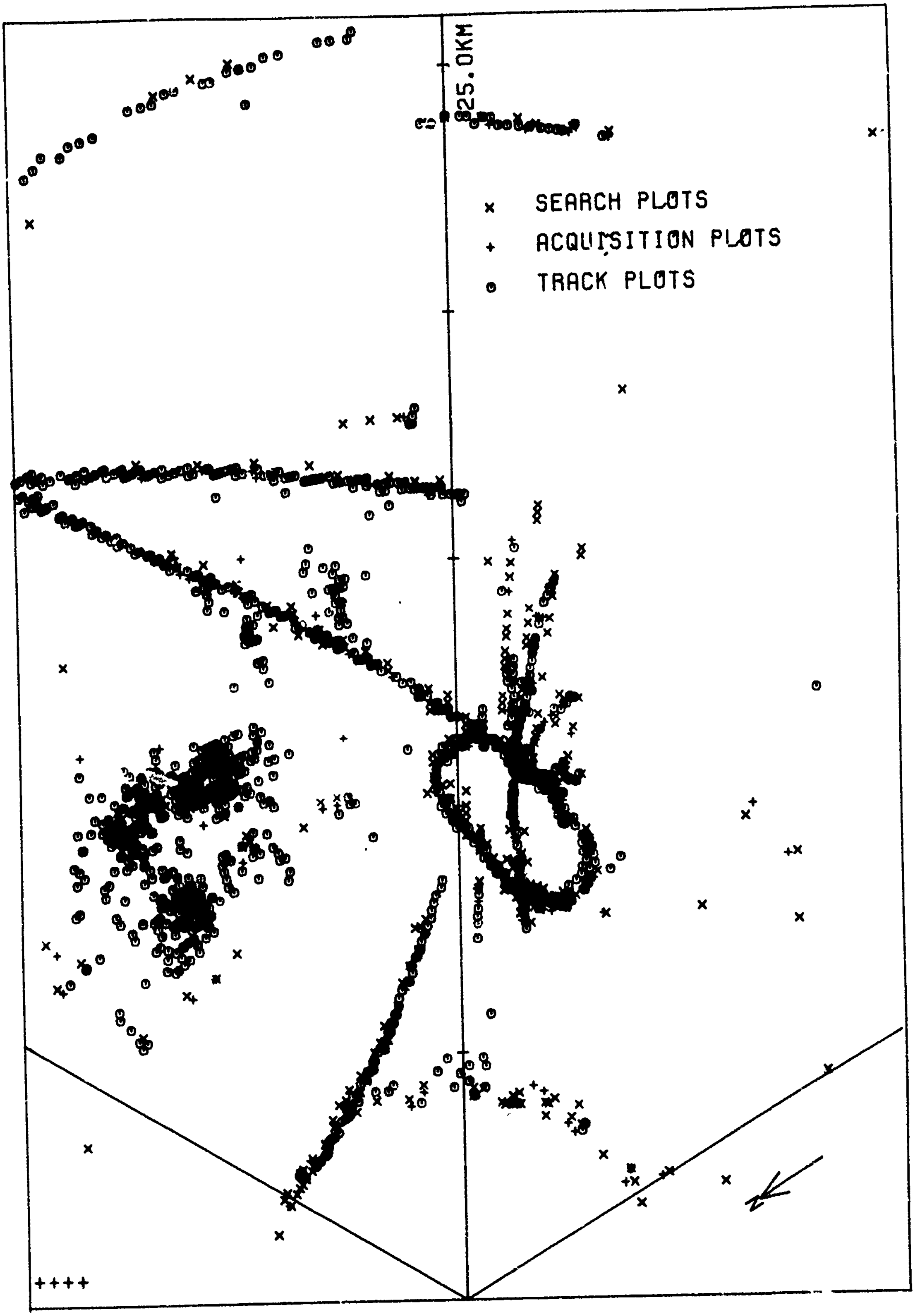


Fig. 9 Helicopter Test Flight

DISCUSSION

R. Des Rotours, France

What time is allowed for search, initiation, tracking?

Author's Reply

During that helicopter test flight, a standard search pattern was employed. Only one beam was used. Tracking one target demands about 10 percent of the available time, including some amount of false alarm track initiation in clutter areas.

DESIGN CONSIDERATIONS FOR RADAR TRACKING IN CLUTTER

by

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SUMMARY

Clutter is still an enormous problem in the radar field. In attempting to solve this problem different techniques are applied to decrease the number of false plots which are presented to the tracking logic without decreasing too much the number of real plots, i.e. the plots from aircraft. However, it is impossible to remove all the false plots and retain the true plots only. So the performance of an automatic tracking logic in a mixed environment of false and real plots has to be studied. This is the subject of the study.

The problem is investigated with Monte Carlo simulation. In order to gain insight into this complex problem the simulation is kept simple. (It is stated by the author that large scale Monte Carlo simulations certainly produce results and reports, but very seldom give insight into the mechanics of the tracking process).

The investigation is a sensitivity analysis for five important parameters: -

(1) Radar detection probability

(2) Clutter density

(3) Smoothing parameters

(4) Gate size

(5) Maximum number of consecutive misses

One of the questions which needs investigation is: -
What is the maximum clutter density in which targets are reliably tracked? The word 'reliably' poses the question of a performance criterion, which judges the goodness of tracking. Recommendations are given for the various parameters α-β, gate size and miss. sequence counter.

This analysis will help in the design of a tracking logic of an automatic Air Traffic Control System. The study has served as a Doctoral Thesis at the University of Bremen (West-Germany).

1. INTRODUCTION

Clutter is still an enormous problem in the radar field. In attempting to solve this problem different techniques are applied. For instance: special receivers are built, Moving Target Indicators (MTI) are improved, the effect of polarisation is investigated, and special coding techniques are invented to decrease the number of false plots which are presented to the tracking logic without decreasing too much the number of real plots, i.e. the plots from an aircraft.

However, it is impossible to remove all the false plots and retain the true plots only. So the performance of a tracking logic in a mixed environment of false and real plots has to be studied.

In Chapter 2 the assumptions which apply to this study are listed and discussed. The performance of a tracking logic in clutter depends on the evaluation criteria. These criteria are discussed in Chapter 3.

The problem will be investigated with simulation on a digital computer (Chapter 4). The investigation is a sensitivity analysis for five important parameters: -

(1) Radar detection probability

(2) Clutter density

(3) Smoothing parameters

(4) Gate size

(5) Maximum number of consecutive misses.

The analysis will help in the design of a tracking logic of an automated Air Traffic Control System, which will remove some of the routine work of the controller. In particular, the study will produce the following results (which are dependent on the indicated parameters):

(1) The maximum clutter density in which tracking can be reasonably continued

(2) The optimum gate size.

A Bibliography on radar tracking in clutter concludes the study.

2. ASSUMPTIONS

Some of the assumptions adopted for this study are necessary to keep the mathematical model transparent and relatively simple. Other assumptions are made to restrict the scope of the study. The assumptions are listed under five headings.

2.1 TARGET

The model is described relative to a two-dimensional Cartesian coordinate system.

One aircraft moves at a constant speed in a straight line. The equations of motion of the target are

$$x = V_x t + x_o$$

$$y = V_y t + y_o$$

where x and y are the Cartesian coordinates of the target position, V_x and V_y are the velocity components in x and y, t is the time.

The total flight of the aircraft is in the radar coverage.

2.2 RADAR

It is assumed that only primary 2-D radar information is available, i.e. there is no identification and/or height. It is further assumed that only position is measured.

It is assumed that the measurement errors in position are normally distributed around the target position, uncorrelated in x and y, uncorrelated from scan to scan, with an equal standard deviation in x and y ($\sigma_x = \sigma_y = \sigma$), (a radially symmetric distribution).

The radar scan time is fixed and equal to T. The measurement interval is assumed equal to T. The probability of detection (blip-to-scan ratio) P_d is constant during the initiation of the track ($P_d = 1$), P_d is also constant during the aircraft flight through clutter. This will not be true in practice. Many complex factors influence the radar range equation. However, this assumption can be justified for areas of the total coverage.

2.3 CLUTTER

It is assumed that the aircraft enters a clutter region. From then on the aircraft flies through clutter.

It is further assumed that the average density of the clutter plots in this region is constant, and there is no correlation between clutter plots from scan to scan. The clutter density D is given as the average number of plots per unit area. σ is chosen as the unit of length (σ is the standard deviation of the radar measurement error in x or y). So the unit of the clutter density is σ^{-2}.

It is assumed that the clutter plots are uniformly random distributed over the area.

The distance r from a position to the nearest clutter echo has a Rayleigh density function.

$$p(r) = 2\pi \, D \, r \, e^{-\pi D r^2}$$

Both noise and clutter produce false plots. It is assumed in this study that the noise plots have the same characteristics as clutter plots. The total effect of noise and clutter can then be expressed in one combined density, which will be called in this study the clutter density.

2.4 TRACKING LOGIC

It is assumed that the tracking logic uses only one fixed α-β pair of smoothing constants.

The tracking program is a two-dimensional track-while-scan logic. It is assumed that there is no interaction between tracks. There is one circular gate considered (radius R). The gate size is independent of the number of missed plots.

Within this gate the nearest plot to the predicted position (which originates either from the target or from the clutter) is considered by the tracking logic as the plot position P_n.

The α-β tracking logic can be described with the following recursive equations (Simpson, 1962):

$$C_n = F_n + \alpha (P_n - F_n)$$

$$V_n = V_{n-1} + \frac{\beta}{T} (P_n - F_n)$$

$$F_{n+1} = C_n + TV_n$$

where C_n = corrected track position taking account of the plot arriving on the n^{th} scan.

V_n = corrected track velocity, taking account of the plot arriving on the n^{th} scan.

P_n = position of plot arriving on the n^{th} scan.

F_n = predicted (extrapolated) position of the track, appropriate to the n^{th} scan.

T = scan period.

α = position smoothing constant.

β = velocity smoothing constant.

If a track does not correlate with a plot this track will be extrapolated using current estimates of the speed in x and y of the target. Branching of tracks is not considered.

It is further assumed that all tracks have been automatically initiated in a clutter-free area. In the clutter area initiation is prohibited.

2.5 TRACKING COMPUTER

It is assumed that there are no execution time limitations for the tracking program and the computer core size is sufficiently large to cope with the total number of plots and the tracking program.

3. PERFORMANCE CRITERIA AND DESIGN

3.1 INTRODUCTION AND DEFINITION

The process of tracking has been briefly discussed in the introduction. Two parts in this process can be distinguished.

(a) Initiation

(b) Tracking

During initiation the logic tries to find out within certain statistical confidence limits if the string of plots under consideration belongs to a clutter plot sequence or to an aircraft path. The process of initiation is in fact a decision process. During this process the logic tries to find out if the received plots can be fitted by a clutter plot distribution, or by a set of aircraft path measurements. The end of the initiation process is a decision.

The decision is either

(a) The plot sequence originates from false plots, or

(b) The plot sequence is from an aircraft.

With a properly designed initiation logic this is the optimum decision to be made at this scan. (It may turn out that the decision was wrong,but this is due to the confidence limits of the particular initiation logic).

The initiated track is then displayed to the air traffic controller. He uses the information of this track as if it were an aircraft. The tracking process is now in stage (b): tracking.

The tasks of the two processes are quite different. In the initiation process an optimum decision between true or false has to be made, however, in the tracking process it is assumed that a valid track exists and the task is to follow this track optimally. Any consideration on optimization of the tracking process should take account of the fact that a decision has been made at the end of the initiation process. So it should not be attempted to optimize the whole process of initiation and tracking. The initiation process should be optimized to find out which initiation logic yields the best decision. And next, the tracking process should be optimized. The two processes are not independent, but the optimum for the initiation process does not necessarily yield the optimum for the tracking process.

The problem which will be studied is radar tracking in clutter. One of the questions which needs investigation is: What is the maximum clutter density in which targets are reliably tracked? This word 'reliably' poses the question of a performance criterion, which judges the goodness of tracking. Somehow, an indication is needed in which clutter density tracking cannot be performed, in which densities the performance is reasonable, and in which densities the tracking is good.

The performance criterion which will be used in this study is: a track is considered valid (real) if the distance between track and target is less than or equal to the radius of the gate. If this distance is larger than the radius of the gate then this track is a false track.

Something has to be added to this criterion. An air traffic controller who watches the display of tracks will detect from time to time situations which will need his assistance. This assessment of the air situations is based on the displayed tracks. Some of these tracks are valid and thus represent an aircraft path, but some of these tracks are false. If too many tracks on the display are false, the air traffic controller will lose confidence in the tracking logic.

It seems appropriate for the design of a tracking logic to allow for some false tracks, otherwise it is difficult to declare tracks. One of the specifications for the design of a tracking logic should be that the number of mistakes (false tracks) is kept sufficiently low. This task is similar to the type II error in statistical sample testing, and in radar detection. (Hoel, 1965).

This consideration on the maximum tolerable number of false tracks is a constraint in the optimization of the probability of maintaining real tracks. (Hönerloh, 1971).

This study does not extensively deal with the problem of optimization of a tracking logic. However, the optimization should recognize the existence of false tracks.

There are other more complex sets of performance criteria. Leth-Espensen (1964) for instance discusses a criterion which combines in one figure of merit the total performance of a tracking logic. This results in a rather complex formula. This formula tends to hide the basic structure of statistical testing. This structure is that there are type I and type II errors. The weights which are given to these two types of error depend on the particular application.

3.2 BLIND PREDICTION

Results of the performance of tracking in clutter are compared with the performance of blind prediction (sometimes known as dead reckoning). When the aircraft enters the clutter area then, as described in the previous section, a plot in the gate is used to update the current predicted position and speed. The plot position which was used could have been a clutter plot or an aircraft plot, but this is not known to the tracking logic.

In the case of blind prediction the aircraft enters the clutter area and from then on all plots are rejected for updating of the track. So at the end of the initiation process the tracking process has estimated a velocity.

What is the probability that the track will survive during the pass through the clutter area, without any update of this estimated velocity?

Assuming a stationary tracking process (i.e. an infinitely long series of uninterrupted plot detections) then the variance σ_k of the predicted position k scans ahead with respect to the aircraft position equals. (Simpson, 1962).

$$\frac{\sigma_k^2}{\sigma^2} = \frac{2(\frac{2\alpha-\beta}{2} + \beta k)^2}{\alpha(4 - 2\alpha - \beta)} + \frac{\beta}{2\alpha}$$

where σ, α, β are defined in Chapter 2.

4. SIMULATION APPROACH

4.1 DESCRIPTION

With the assumptions made in Chapter 2 and the performance criterion in Chapter 3 it is feasible to study the problem of radar tracking in clutter by Monte Carlo simulation on a digital computer. The assumptions lead to a fairly simple description of the problem. This is deliberately done in order to keep the approach transparent.

In the initiation phase plots are received from a straight moving aircraft, during N consecutive scans. Each scan the plot position is a randomly disturbed aircraft position. The disturbance has a normal distribution, which is limited to $\pm 3\sigma$ to restrict the influence of excessive values. The actual disturbance is drawn from a (pseudo) random number generator. During these N scans the probability of detection is equal to 1. Each scan the predicted position is calculated with the recursive tracking equations using the α-β smoothing constants.

After N scans the aircraft enters a clutter area of a given clutter density. The tracking logic has a fixed gate and the smoothing constants are equal to those during initiation. The blip scan ratio is fixed and not necessarily equal to 1.

It is thus possible that clutter plots fall inside the circular gate around the predicted position and compete in the allocation phase with the plot from the aircraft (if present).

The plot which is closest to the predicted position is allocated to the track. This tracking process is continued for 100 scans. Then the process for this track is stopped.

A new aircraft path is generated. During N consecutive scans the initiation of a track takes place, the track enters the clutter region and so on. This is repeated 1000 times.

The maximum number of consecutive misses M (i.e. no plots in the gate) is accumulated for the track during its life in order to assess the effect of a limit to M.

Each scan the evaluation criterion is applied to the track, i.e. if the distance of the predicted position of the track from the aircraft path is larger than the radius of the gate, then the track is declared a false track.

This simulation with the assumptions in Chapter 2 is put into a computer program. The listing of the program written in FORTRAN IV for a CDC-6400 computer is given in Reference 7.

The following sets of parameters are selected:

Detection probability P_d	0.6, 0.8, 1.0
Smoothing constants (α, β)	(0.50, 0.16), (0.75, 0.45)
Gate radius (σ)	2.5, 5, 10
D clutter density (σ^{-2})	0.001, 0.003, 0.01, 0.03, 0.1
M (maximum number of consecutive misses)	1, 2, 3, 4, 5, 6

The velocity smoothing constant β is related to α by $\beta = \frac{\alpha^2}{(2-\alpha)}$. (Benedict, Bordner, 1962)

Some results of this parametric investigation are given in Figures 1 - 8. For each set of parameters there are two figures. One gives the number of tracks which survive, the other figure gives the number of false tracks, both as a function of scans in clutter.

The parameters a/b along the curves indicate clutter density/M, if only one parameter is written then this indicates the clutter density, and M=∞.

4.2 CONCLUSIONS

4.2.1 Real Track Maintenance

If, for a moment, it is forgotten that the false track rate is an essential part of the evaluation criterion for the performance of radar tracking in clutter, then the following conclusions can be drawn.

1. Blind prediction

For a fixed α-β logic blind prediction leads to poor results. This is also the performance of the tracking logic, if the radar does not receive plots during a number of scans (for instance a Doppler blind region).

2. Gate size

In general the performance improves for increasing gate sizes. The difference between a radius of 5σ and 10σ is rather small. The results indicate that a gate radius of 2.5σ is too small.

The optimum gate size depends on probability of detection, clutter density, α-β constants, the maximum number of consecutive misses and (although not shown) on k (scan number). To be more specific: the optimim gate size is larger for the larger P_d, all other parameters being equal. This puts a conclusion of Sea (Reference 6) concerning gates into perspective.

For P_d <1 an optimum gate size is expected. If a track does not correlate with a (real) plot in the gate then a false plot might steal the track. This will generally change the velocity of the track, and the track might become a false track. This more likely to happen for smaller P_d, larger clutter densities, and larger gate sizes.

For P_d = 1 (Fig. 1, 2, 3, 4)

The performance improves for increasing gate size, and approaches asymptotically a constant value. A larger gate size is required in order to arrive at this asymptote for larger clutter densities and larger (α-β) smoothing constants.

For P_d = 0.8

There is an optimum gate size which hardly depends on clutter density. The optimum gate size is smaller for the α-β pair (0.50, 0.16), compared with α-β (0.75, 0.45). The first α-β constants yield a wider maximum.

For P_d = 0.6

There is an optimum gate size which depends on clutter density. The optimum gate size is smaller for larger density. This gate size hardly depends on (α-β).

3. Sample size

The smoothness of the curves indicates that a reasonable sample size is selected.The difference in performance at scan 0 for a given set of parameters is entirely due to the limited sample size.

4. Smoothing parameters

It can easily be concluded that the α-β pair (0.50, 0.16) yields a better performance than the pair (0.75, 0.45). This is because the first smoothing constants are good smoothing constants for a straight flying target given that a good position and velocity estimate were obtained in the initiation process. The second set of smoothing parameters indicates the uncertainty about the predicted position and velocity, and more weight is given to the radar plot position than to the predicted track position. The plot information is accepted almost unsmoothed and the tracking process is much more susceptible to stealing by clutter plots. Consequently the performance decreases rapidly.

5. M the consecutive number of misses

With M unlimited, then the number of false tracks which originate from a real track increases rapidly with increasing clutter density, increasing scan number, larger α-β constants, and smaller detection probability. For instance, for a P_d = 0.8, α = 0.50, β = 0.16, a gate radius of 10σ, and tracking during 30 scans, density 0.003, 1000 - 750 = 250 tracks are false. (Fig. 5). A limit to M, for instance M=3, will reduce this number considerably, (Fig. 6), without a major effect on the probability of maintaining real tracks. (Fig. 5).

6. Probability of detection P_d

The results indicate that the detection probability has considerable effect on the performance of a tracking logic in clutter.

7. Maximum clutter density

Based on a required minimum probability of .5 of maintaining a track during k scans the following conclusions can be drawn:

(a) P_d = .6, gate = 10σ, (α-β) = (0.50, 0.16)

If a target has to be tracked during k=20 scans through clutter with the given parameters, then the maximum density equals ≈ 0.005.

If a target has to be tracked during k=40 scans under the same conditions, then the maximum density is decreased to ≈ 0.002.

(b) P_d = .8, gate = 10σ, (α-β) = (0.50, 0.16)

Mutatis mutandis the maximum density for k=20 scans equals ≈ 0.1, and for k=40 scans equals ≈ 0.005 (Fig. 5).

(c) P_d = 1.0, gate = 10σ, (α-β) = (0.50, 0.16)

Mutatis mutandis the maximum density for k=20 scans is ≈ 0.1, and for k=40 scans ≈ 0.05.

4.2.2 Total Evaluation Criterion

However, the false track rate is an essential part of the evaluation criterion. The use of the figures for the design of a tracking logic is best explained by an example.

Suppose 18 aircraft per 4 hour fly straight through a clutter area with a density of 0.003 for 40 scans. Suppose further that a maximum false track rate of 1 per half hour is tolerable for an air traffic controller, and further the detection probability is .8, and due to manoeuvre considerations the gate size is proposed to be 10σ.

Then from Fig. 6 and Fig. 8 it follows that with M=3 this design is feasible for both (α-β) pairs. Fig. 5 and Fig. 7, respectively, give the probability of real track maintenance. If the detection probability is only .6 then it is concluded that for (α-β) = (0.75, 0.45) the false track rate is too high. Consequently, if this (α-β) pair is needed, some compromise has to be made.

4.3 NON-STRAIGHT FLIGHT OF AN AIRCRAFT

If the target does not move straight as is assumed in this study, (Section 2.1), the conclusions as drawn in Section 4.2 are not valid.

In order to know the performance of a tracking logic in clutter for non-straight flying aircraft it is necessary to change the equations of motion of the aircraft in the computer model. This will yield another set of pictures. However, some preliminary conclusions can be drawn.

If an aircraft does not move straight and there is no apriori knowledge about the aircraft manoeuvre, then (relatively) large gates are needed. The same reason leads to the larger α-β smoothing constants.

So, as a first approximation, it is expected that the performance will look like the performance found for the gates with a radius of 10σ and α-β = (0.75, 0.45).

4.4 APPLICATION OF THE CONCLUSIONS

It is clear from the preceding conclusions that the possibility of a detection probability not equal to 1 and a number of false plots not equal to 0, can have a severe influence on the performance of a tracking logic. The amount of influence depends on P_d, clutter density, (α-β), gate size, maximum number of consecutive misses, and clutter area extension.

It is rather difficult (as indicated in Sections 2.2 and 2.3) to measure P_d, clutter density and the clutter area. So it is equally difficult to apply the conclusions of Section 4.2 to a tracking logic.

Nevertheless, these conclusions give constraints to the design of a tracking logic, and indicate a working area in which the tracking will have a certain minimum performance. These results will thus quantitatively assist the designer in discussing requirements for the performance of tracking logics in clutter. More results and details of the Analysis are presented in Reference 7.

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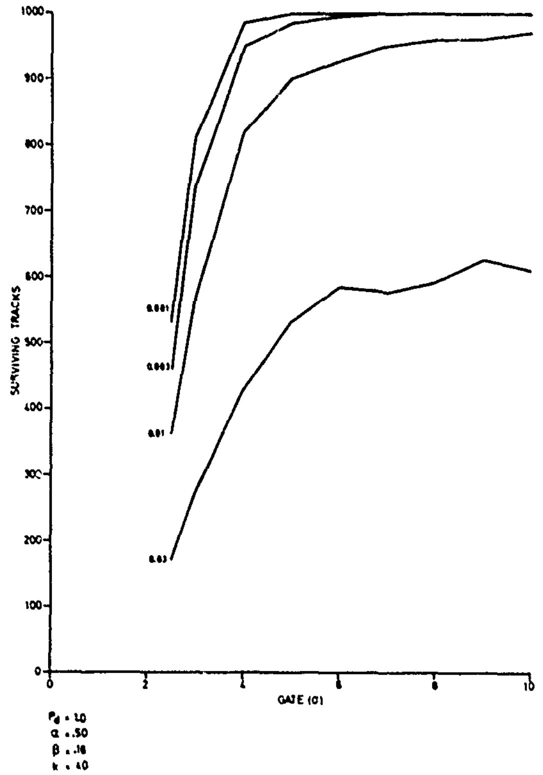

Fig. 1 Number of surviving tracks at scan k=40 as a function of the gate size (M = ∞)

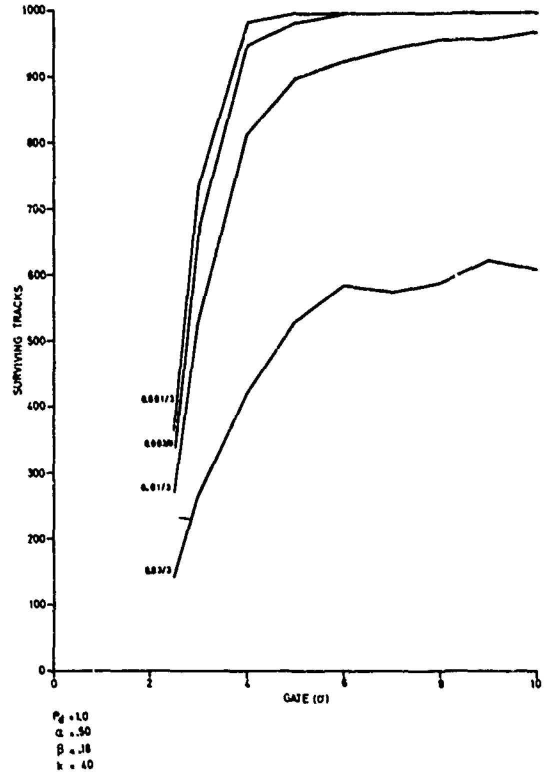

Fig. 2 Number of surviving tracks at scan k=40 as a function of the gate size (M = 3)

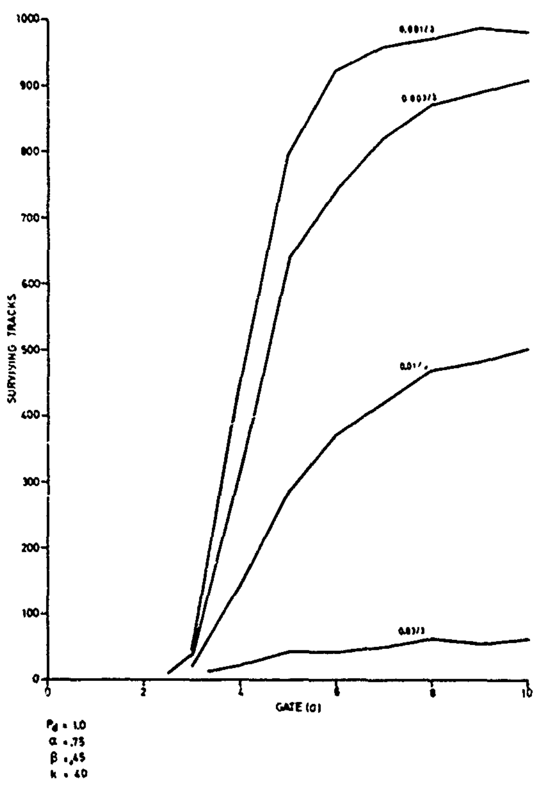

Fig. 3 Number of surviving tracks at scan k=40 as a function of the gate size (M=3)

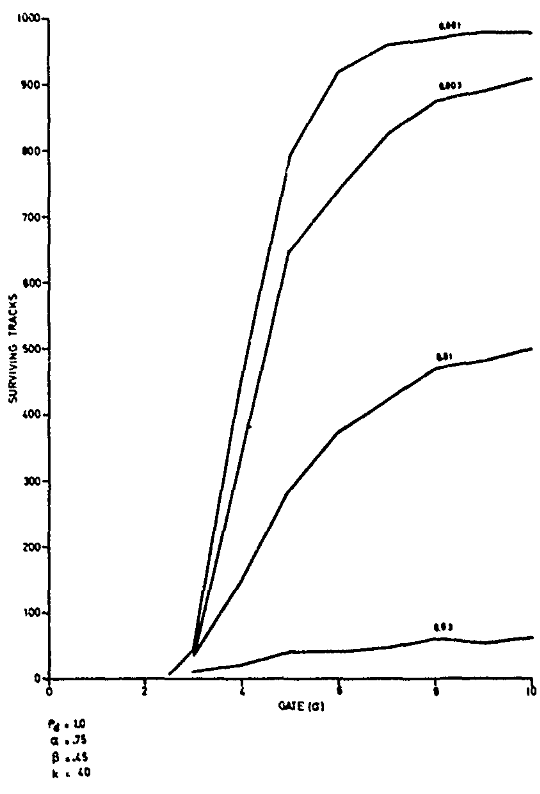

Fig. 4 Number of surviving tracks at scan k=40 as a function of the gate size (M = ∞)

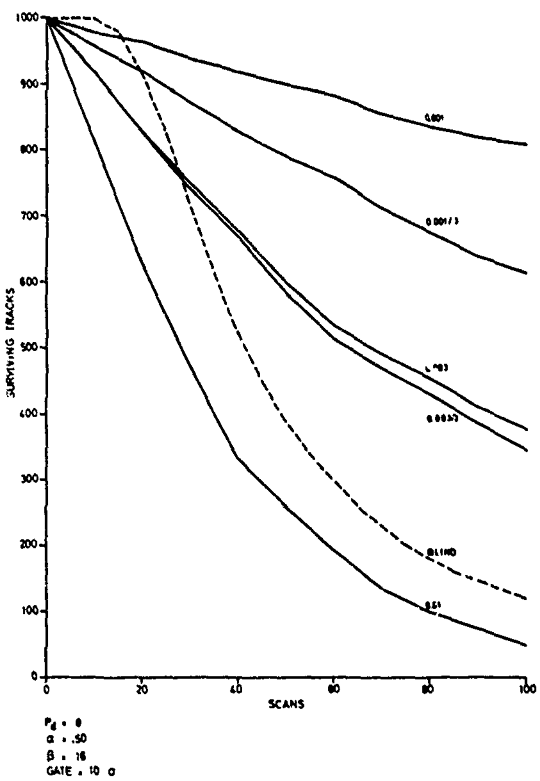

Fig. 5 Number of surviving tracks as a function of the number of scans in clutter

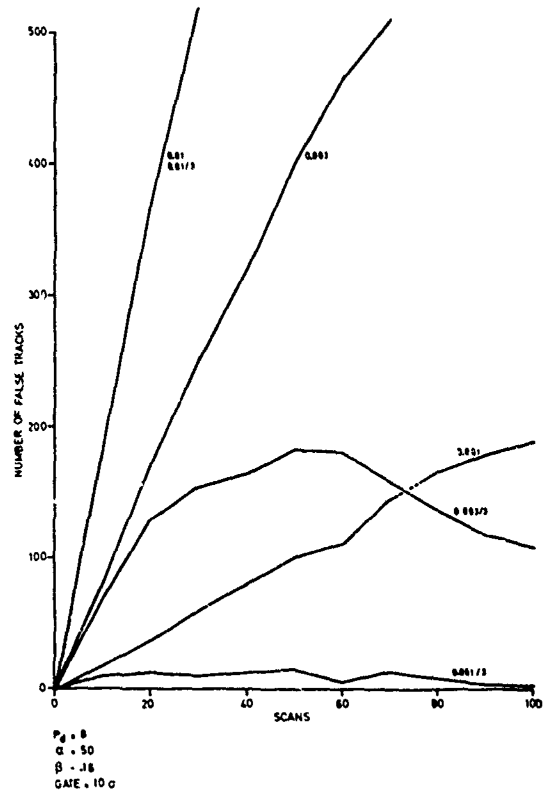

Fig. 6 Number of false tracks as a function of the number of scans in clutter

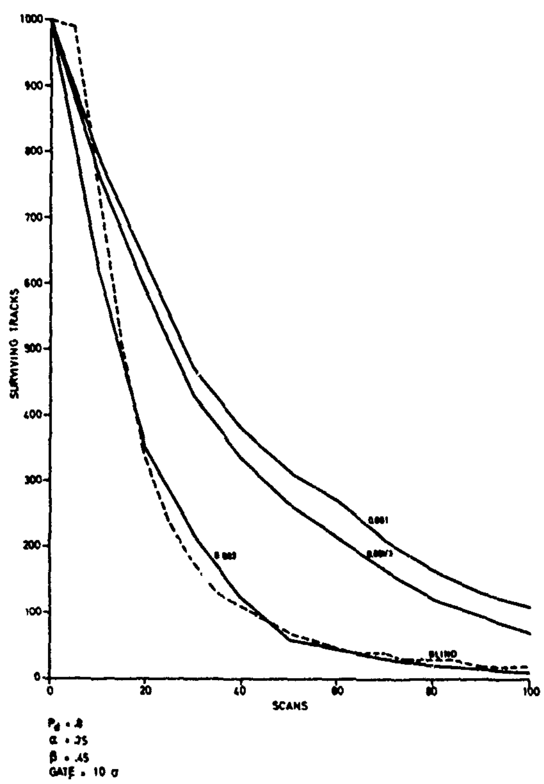

Fig. 7 Number of surviving tracks as a function of the number of scans in clutter

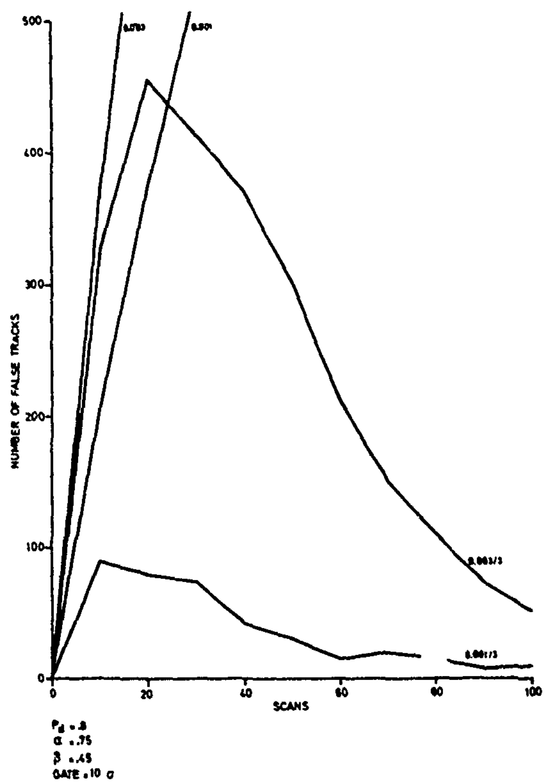

Fig. 8 Number of false tracks as a function of the number of scans in clutter

DISCUSSION

G.Binias, FRG

Have you examined tracking filters other than α-β filters with fixed parameter values?

Author's Reply

The results of Figure 15 were obtained by selecting between two fixed α-β sets. It would, however, be relatively easy to implement an adaptive α-β filter, which adjusts the smoothing constants by using the observed hit-miss sequence.

G. van Keuk, FRG

You assumed uniformly distributed clutter. This is not correct in sensor oriented nor in x-y coordinates. Your theoretical investigation is only locally correct. Have you studied any other tracking strategies or have you only concentrated on the nearest neighbor strategy?

Author's Reply

The assumed clutter-distribution and the tracking strategy are selected to make the computer simulation simple. The object of the study was to create a transparent model which shows the influence of some important parameters.

E.Brookner, USA

Figures 14 and 15 show the average track life first decreasing and then increasing as the clutter density increases from 10^{-4} to 10^{-1}. Could you explain physically why this happens?

Author's Reply

The basic trend of all the curves is that the average track life decreases as clutter density increases from 10^{-4} to 10^{-2}, thereafter the average track life generally increases.

The reduction in track life occurs because false plots (clutterplots) capture the track and create an erroneous track-velocity which leads the track astray. When the distance between the track and the actual target-path becomes more than R then the track is a false track. This track-stealing process happens more often for increasing clutter density. In Chapter 5 of Reference 7 some analytical models are given which clearly indicate this effect of clutter-plot-stealing.

For the larger clutter densities ($> 10^{-2}$) it is almost certain that a clutterplot falls in the gate. The density is so large that the clutterplot is close to the predicted position. Generally the track will stay close to the target path and -- on the basis of the selected evaluation criterion – it seems that high clutter densities increase average track life!

It should be noted, however, that average track life of order 20-scans is generally not acceptable in Air Traffic Control applications.

F.Herzmann, FRG

On your last vugraph (Figure 15) the curves are numbered 1, 2, 4 and 1/2. What does 1/2 mean?

Author's Reply

The parameter 1/2, 1, 2, 4 refers to the update rate of the tracks: 2T, T, 1/2T and 1/4T.

F.Herzmann, FRG

Do all participating radars have the same position?

Author's Reply

The location of the radars is not simulated. The update rate was increased from T to say 1/4T. The updates were evenly distributed in time. The detection probability and the clutter density can be specified separately for each radar. Track life was studied when four radars detect the target. For the simulation it is not relevant where these radars are located, provided that reasonable update-time, P_d and clutter densities are used as input parameters.

ADDITIONAL MATERIAL INCLUDED IN THE ORAL PRESENTATION

The radar returns were assumed to be independent from scan to scan for the previous Figures. If we remove this assumption and introduce a correlation coefficient c then we find the following results:

for $\alpha = 0.50$, $\beta = 0.16$:

Figure 9:	Surviving tracks	$P_d = 0.8$	$C = 0.25$
Figure 10:	False tracks	$P_d = 0.8$	$C = 0.25$

and for $\alpha = 0.75$, $\beta = 0.45$:

Figure 11:	Surviving tracks	$P_d = 0.8$	$C = 0.25$
Figure 12:	False tracks	$P_d = 0.8$	$C = 0.25$

If we compare these results with the previous ones, we observe that correlation from scan to scan is undesirable. We can also see the effect of gate size and use the simulation to find the optimum size.

Figure 13: Surviving tracks/gate size/scans

If the results for the number of surviving tracks are transformed into an average track life then we find.

Figure 14: Average real track life $P_d = 0.8$

We can clearly see the influence of the correlation coefficient. We also observe the influence of clutter density.

Back to the uncorrelated scan-to-scan radar returns. I want to show you one result of multi radar-tracking.

Figure 15: Average track life $P_d = 0.8$

The aircraft is observed by 1–4 radars. The radar returns are equally spaced. The gate size is no longer fixed and the α/β values vary, dependent on the distance between measured plot and predicted track position. The Figure shows the improvement in average real track life for an increasing number of radars.

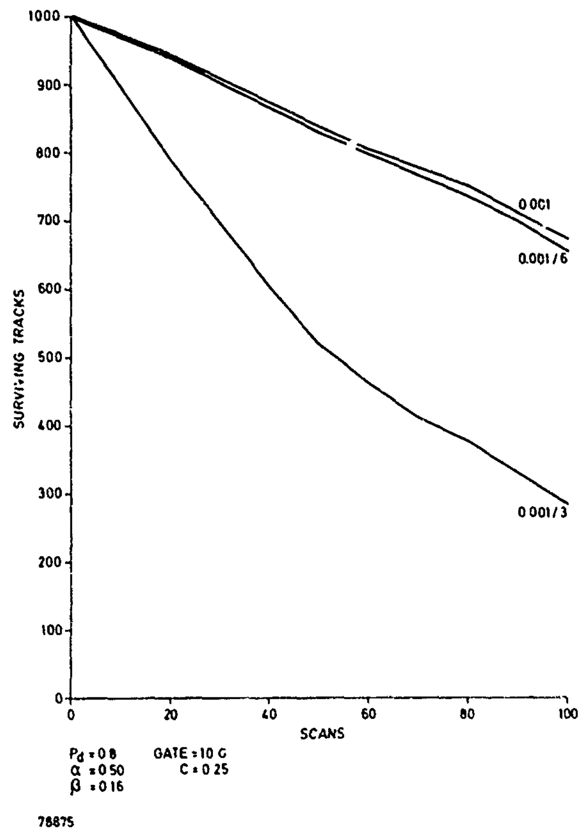

Fig.9 Number of surviving tracks as a function of the number of scans in clutter (C = 0.25)

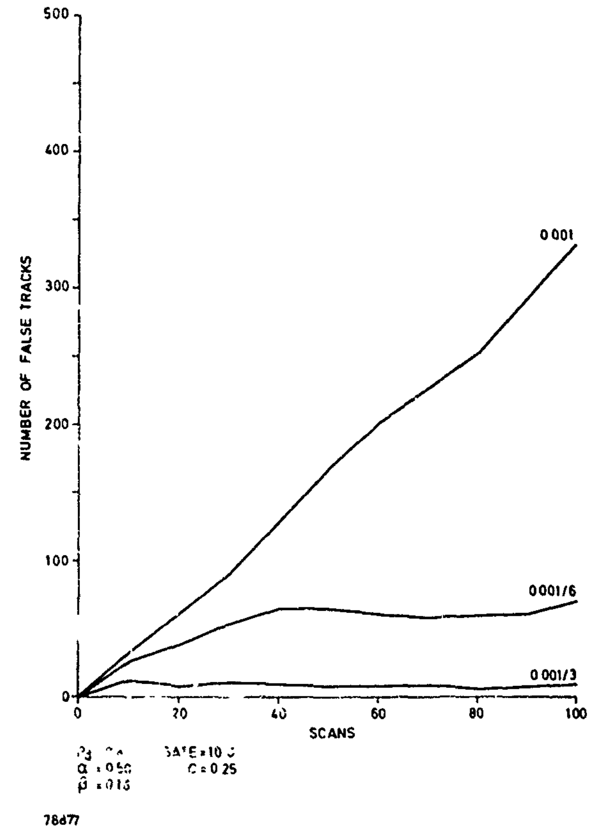

Fig.10 Number of false tracks as a function of the number of scans in clutter (C = 0.25)

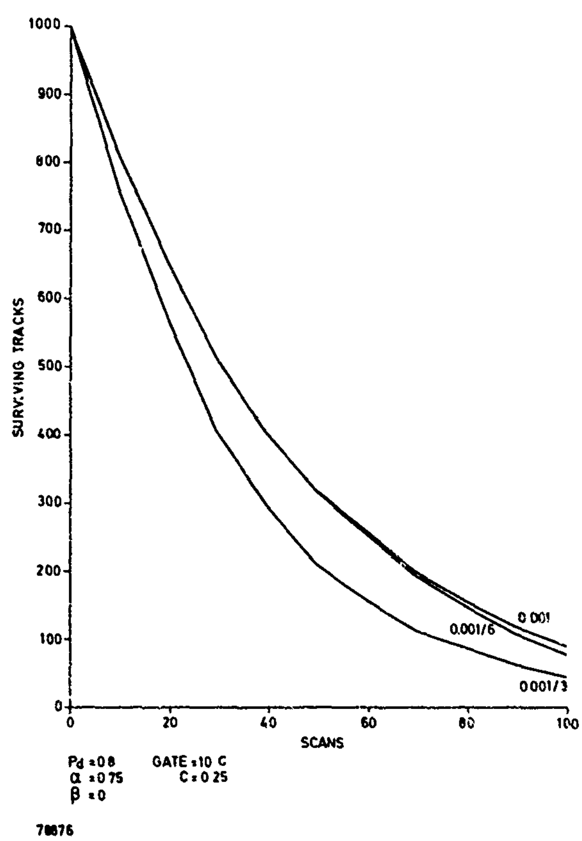

Fig.11 Number of surviving tracks as a function of the number of scans in clutter (C = 0.25)

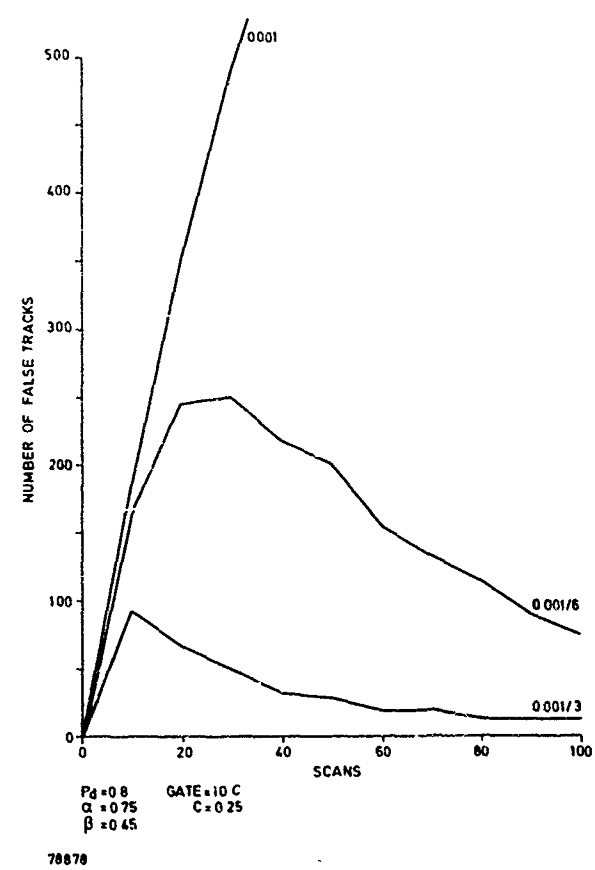

Fig.12 Number of false tracks as a function of the number of scans in clutter (C = 0.25)

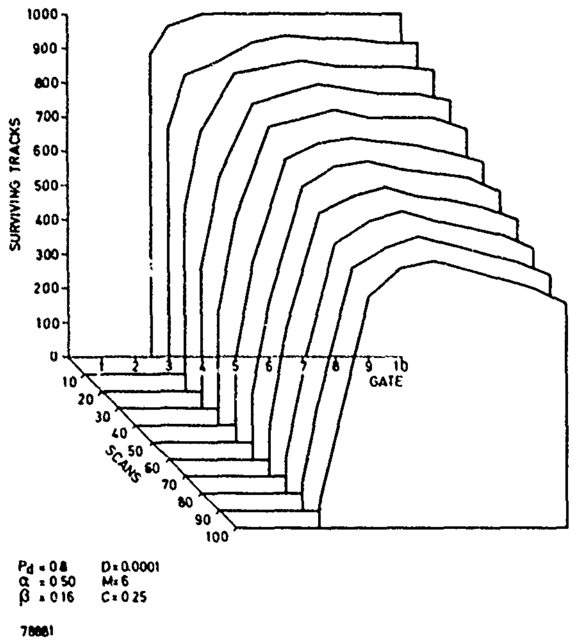

Fig.13 Number of surviving tracks as a function of the number of scans in clutter, and as a function of the gate size

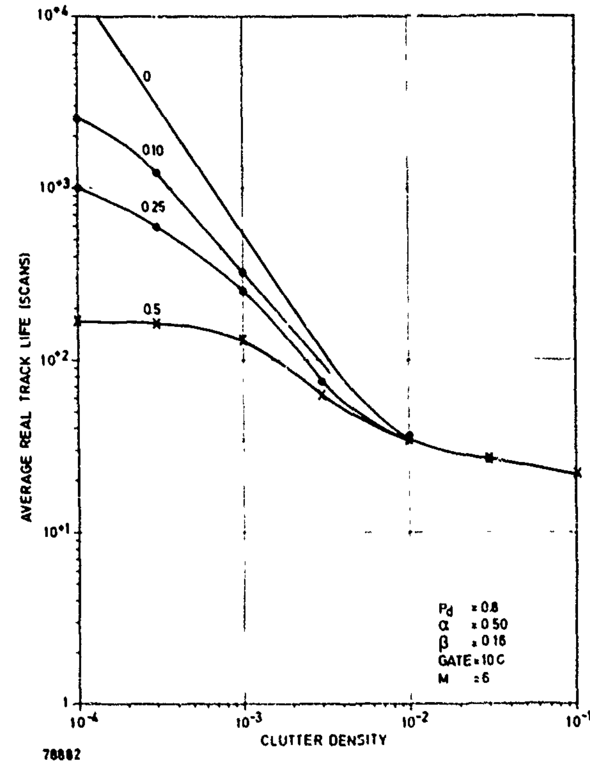

Fig.14 The average real track life as a function of the clutter density (parameter for the curves is the correlation coefficient)

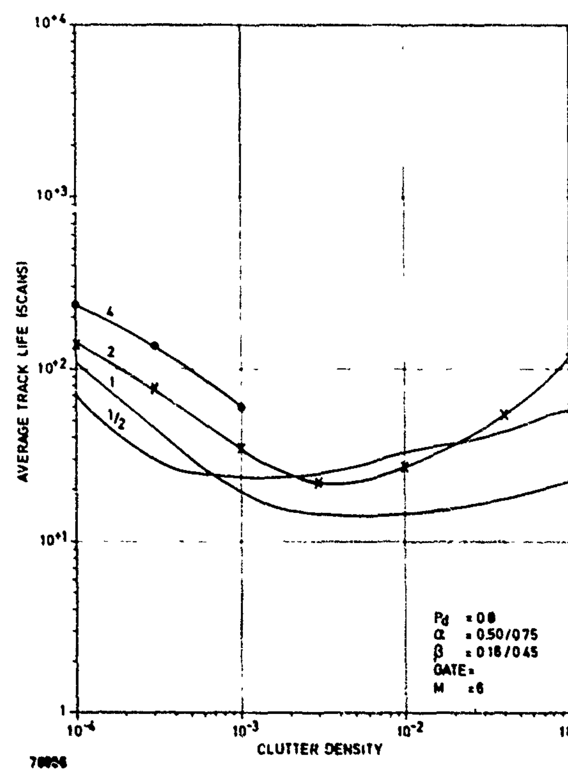

Fig.15 The average real track life in a multi-radar environment (parameter for the curves is the update rate)

SOME ASPECTS OF MULTI-RADAR TRACKING

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SUMMARY

This paper presents three different aspects of a multi-radar simulation study aimed at determining the best tracking organisation and algorithms.

The first aspect is that of tracking groups of aircraft which are not all individually resolvable. Simulation showed that a manually defined quadrilateral enclosing the aircraft could be used for filtering the formation while tracking was performed by evaluating the centroid of the group and tracking it as a single entity.

In any tracking system height is required primarily for tactical reasons, but in a multi-radar tracking system it is also required for the co-ordinate conversion of the measured plot position to the common tracking plane. There is therefore an additional requirement to produce accurate height information in order to improve the tracking performance. The height accuracy can, in general, be improved by height filtering and this paper describes a possible algorithm.

The implications of uncoupling the multi-radar Kalman filter are considered in terms of tracking performance. It is shown that under certain circumstances the tracking performance is considerably degraded when an uncoupled Kalman filter is implemented.

1. INTRODUCTION

A study has been completed into the feasibility of automatically correlating primary radar data from collocated and geographically dispersed sensors with over-lapping cover. A recent paper (MORLEY, A.R. and WILSDON, A.S. 1977) reported on the tracking methods investigated together with a description of some of the algorithms used. A trade-off analysis was performed and two methods were favoured. Figure 1a outlines the Distributed Method and Figure 1b outlines the Integrated Method. The Distributed Method can be implemented in either a centralised or decentralised form but the Integrated Method only has a centralised solution.

This paper reports on three topics which received an in-depth study during the work but which have not been previously published. The three subjects are:

(a) Aircraft formation tracking

(b) Height tracking

(c) Decoupling the Kalman filter.

2. AIRCRAFT FORMATION TRACKING

2.1 Introduction

The original simulation study contained no special analysis to deal with aircraft flying in close proximity and this presented a number of problems within the tracking simulation. The major problem area was that of plot-to-track association where the close proximity of individual plots was such that a single plot could appear in the noise gate of more than one track. Additionally, because of limited resolution, the radar itself might not extract a plot from every aircraft for each scan and the pattern of plots was found to vary from scan to scan. It was not always possible to correctly categorise this situation which was greatly aggravated in the auto-initiation area and unnecessarily complex situations arose. The auto-initiation at that stage of the study was being performed on a multi-radar basis and clearly the radars see the aircraft differently depending, amongst other things, on their respective alignments.

A requirement was therefore identified to deal with the situation of close formation aircraft in a separate manner. It is not generally necessary to follow the movement of individual aircraft to determine the overall speed and heading of the group. The other parameter which has operational significance is the number of aircraft within the formation.

A further advantage of formation tracking is that it can be invoked when the track capacity of a system is in danger of saturation. Aircraft with similar position, speed and heading can be grouped and reduced to a single track, freeing numbers of track stores.

2.2 Initiation

The initiation of formation tracking was judged to be most effectively carried out by a manual process. Particular problems encountered in the normal association process can be flagged up as warnings to an operator but the automatic delineation of the formation boundary has not been considered practical.

The simplest boundary to superimpose over the formation would be a circle. This would also be the simplest shape to convert between the mono-radar and multi-radar tracking planes. However, it is not practical in terms of any relationship between the formation shape and its boundary. It was decided that a quadrilateral was more convenient and fairly simple shape to work with. The operator is required to manually designate four points on his display which define the quadrilateral. The shape, but not orientation, is preserved during tracking unless manually re-defined. The definition of the quadrilateral should allow for radar plot measurement errors.

The formation quadrilateral is initially defined in system co-ordinates so that each radar covering the formation will use the same shape quadrilateral. Every scan, those plots falling within the quadrilateral are used to re-determine its centroid on a mono-radar basis, simply by averaging the x and y measurement components.

A problem then arises as to how to initiate the speed and heading of the formation. Having defined the shape of the quadrilateral it would not be practical to re-define it. One possible technique is to assume that mono-radar tracks have previously been auto-initiated within the formation and manually inject the speed and heading of such a track. A more rigorous method would be for the operator to crudely indicate a centroid on the next scan so that the quad-rilateral can be positioned to catch all the necessary plots. Computation of the second centroid allows the initiation of the formation track's speed and heading.

It should be understood that the centroid of the plots falling within the quadrilateral is unlikely to coincide with the centroid of the quadrilateral, the latter not being used in the treatment.

It has been found convenient to work with the x-y displacements of each corner from the formation centroid. Displacements derived from the first centroid determination are used on the next radar scan with the manually designated formation centre to align the original quadrilateral for collecting the plots. Thus, the manually designated formation centre does not contribute to the subsequent track formation.

2.3 Association

The association process is necessarily different from that of discrete aircraft (MORLEY, A.R. and WILSDON A.S. 1977) because the formation quadrilateral can overlap a number of 22.5° association sectors. Prior to the normal mono-radar association procedure being called up, all plots are tested to establish if they fall within a crude R-θ gate fixed by the extremes of the quadrilateral modified by an additional manoeuvre component.

The receipt of the first sector message (one every 22.5°) past the formation quadrilateral and azimuth (previously computed), causes the accumulated plots to be processed to determine the new formation centroid. It is this which is passed to both the mono-radar and multi-radar tracking filters.

If the maximum distance an aircraft in the formation can manoeuvre from its linear forecast position in a scan is r then the corners of the manoeuvre gate are computed from the quadrilateral corner displacement ΔX_n and ΔY_n as follows:

$$\Delta X_{n_{man}} = \Delta X_n + R\sin\theta_3$$

$$\Delta Y_{n_{man}} = \Delta Y_n + R\cos\theta_3$$

where

$$R = r/\sin\left[\frac{(\theta_2 - \theta_1)}{2}\right]$$

$$\theta_3 = (\theta_1 + \theta_2)/2$$

$$\theta_1 = \arctan\left[\frac{\Delta X_n - \Delta X_{n-1}}{\Delta Y_n - \Delta Y_{n-1}}\right]$$

$$\theta_2 = \arctan\left[\frac{\Delta X_{n+1} - \Delta X_n}{\Delta Y_{n+1} - \Delta Y_n}\right]$$

In the above equation, manoeuvre values of ΔX_n and ΔY_n are calculated for values of n from 1 to 4. (Where the suffix n-1 is zero, then it is set to 4 and when the suffix n+1 is 5 it is set to 1)

Figure 2 shows an example of the original formation quadrilateral, the manoeuvre quadrilateral and the crude R-θ gate. The R-θ gate is centred on the forecast centroid position.

To determine whether a plot falls within the quadrilateral the following test is carried out:

$$(\Delta X_p - \Delta X_n)(\Delta Y_{n+1} - \Delta Y_n) - (\Delta Y_p - \Delta Y_n)(\Delta X_{n+1} - \Delta X_n) \geq 0$$

for n = 1 to 4. If n + 1 = 5 then n + 1 = 1 where ΔX_p and ΔY_p are the co-ordinates of the plot with respect to the centroid.

The above criteria must be met for all n from 1 to 4. It does not apply for a quadrilateral having a concave corner.

2.4 Tracking

The associated centroid was used to up-date both the local mono-radar track (used for generating association information only) and the system track. The same filters were used as for discrete aircraft formation (see reference) including the manoeuvre test. The major difference between the discrete aircraft tracking and the formation centroid tracking was the measurement variance input to the filters. In the case of discrete aircraft tracking these variances are measurement variances. Assigning the measurement variance to the centroid position, however, is not sufficient and can lead to an intolerably high level of manoeuvre indications. The reason for this is the random (and bias) noise due to effects such as fading. It is necessary to give the centroid an error related to the size of the quadrilateral.

For the multi-radar Kalman filter satisfactory results were obtained with a formation front of 4km when the centroid standard deviation was taken as the measurement noise of a single plot plus 1km.

For the mono-radar filter the problem was not so extreme since less bias was involved. Satisfactory results were achieved by increasing the measurement standard deviations of a single plot by a factor of three and using these as the centroid error. Both the above factors were arbitrarily chosen so that an optimisation exercise could probably result in better stabilisation during non-manoeuvring conditions but nevertheless yield a fast manouevre response. Track manoeuvre in both filters was checked by testing to establish if the measurement centroid fell outside the noise gate made up from the measurement noise and the track forecast error.

Although the Kalman filter was used in its coupled version in the multi-radar case, as a matter of convenience uncoupled filters would give just as satisfactory results.

Track smoothing generally resulted in a track heading change, albeit small and as a result the quadrilateral was also rotated to maintain its original orientation with respect to the centroid heading. This was achieved by performing a rotation on each corner displacement. If Δθ is the heading change, then the new corner displacements are given by:

$$\Delta X_n = \Delta X_n \cos\theta + \Delta Y_n \sin\theta$$

$$\Delta Y_n = \Delta Y_n \cos\theta - \Delta X_n \sin\theta$$

Except in the case of manoeuvre, the heading changes will be very small and therefore small angle approximations can be made to the trigonometrical functions.

2.5 Simulation

The analysis described has been successfully simulated using a group of five aircraft each with a slightly different speed. The most testing section of the flight was a 180° manoeuvre and Figure 3 shows the individual tracks together with the centroid smoothed position and heading vector. The quadrilateral maintained its orientation with respect to the heading vectors.

One aircraft left the raid and this was allowed to automatically initiate a new track.

2.6 Discussion

This section presented the algorithms necessary for tracking a group of aircraft in close formation. The parameter which has not so far been discussed is the number of aircraft in the group. It is likely that each radar will indicate a different number of aircraft depending, amongst other factors, on their relative alignments. It is suggested that the number of plots detected by each radar should receive no processing and that they should be individually presented to an operator together with numbers from previous scans. It is then a manual decision to estimate the number of aircraft involved.

3. HEIGHT FILTERING

3.1 Introduction

Height information is primarily required for tactical reasons but in a multi-radar tracking system it is also required for co-ordinate conversion to a common system plane. Because of the range dependence of height errors, there is generally a requirement to improve on the basic measurement accuracy part cularly at long range by filtering the

measurements. This section describes a height filter and discusses co-ordinate conversion in the absence of height.

3.2 No Height Data

Before discussing the determination of a height value in the absence of height data, it is necessary to define the height boundaries likely to be encountered in a real situation. For the purposes of this paper, the diffraction boundary will be taken as that described by the 4/3rds Earth model. This is very much a simplification of the real World but adequate for the analysis:

$$H_{min} = \frac{3D_{sl}^2}{8R}$$

where D_{sl} is the slant range

R is the Earth's radius

The maximum height will depend on a particular environment. 25km is used in this analysis. This figure is, of course, limited close to the radar by the maximum elevation of the radar which is taken as arcsin (0.4). Figure 3 shows a cross-section of the height limits.

When an elevation measurement α is made, then height is computed from the slant range D_{sl} and R' (=4/3R) as follows:

$$H = \left[D_{sl}^2 + 2R' D_{sl} \sin\alpha + R'^2 \right]^{\frac{1}{2}} - R'$$

This can be simply solved without recourse to a square root routine by using the following equation which is a double iteration:

$$H = H_o (1 - H_o/2R')$$

where

$$H_o = D_{sl} \sin\alpha + D_{sl}^2/2R'$$

In the absence of elevation information, a number of approaches can be made.

At long range it would be possible to assume that an aircraft has recently passed through the diffraction boundary and to take the height at that boundary. The main drawback to this approach is that for a climbing aicraft in a fading situation, the aircraft could cover the total range of possible heights.

A second approach is to build a look-up table of preferred heights at given ranges based on predicted aircraft behaviour.

The approach suggested here is a statistical approach and assumed that an aircraft can be anywhere with an equal probability within the height boundaries. The height chosen is that height which minimises the projected range variance. This means that for aircraft with equal probability of being anywhere in the height range, the accumulated difference between the actual height and the statistical height is minimised. This has been performed on a numerical basis for an orthographic projection and the results curve fitted to give:-

For $D_{sl} > 62\text{km}$

$$H = 15.2 - 0.01D_{sl} + 4.10^{-5} D_{sl}^2 \text{km}$$

$$\sigma_H^2 = 65 - 0.11D_{sl} \text{km}^2$$

For $D_{sl} \leqslant 62\text{km}$

$$H = 0.24D_{sl}$$

$$\sigma_H^2 = 0.015D_{sl}^2$$

These values of height are not the mid-boundary values because the conversion factor from slant plane to orthographic plane is itself a function of range and height. However, they are sufficiently close to the mid-boundary height H_{mid} for this height to be used.

The mid-height variance is given by:

$$\sigma_{H_{mid}}^2 = (H_{max} - H_{min})^2/12$$

$$H_{mid} = (H_{max} + H_{min})/2$$

The above analysis would be more relevant to the case where the expected aircraft distribution in height is not constant such that preferred height bands exist.

3.3 Height Filtering

In the most rigorous approach, the height and its first derivative would become two further elements in the Kalman Filter state vector, so that all the couplings between parameters could be maintained. However, this would result in unjustifiable computer loading and the more usual approach of uncoupling the height is made.

Because aircraft spend a large proportion of their flying time at constant height, considerable improvement can be made in the smoothed height estimation of level flight by implementing a zero order filter. As an example of this, if it takes 10 measurements in a zero order filter to achieve a given smoothed variance, it takes 30 measurements of a first order filter to achieve the same level.

It then becomes necessary to define rules to change the order of filter and these are discussed.

Both filters are least-squares filters, that is, a single component of an uncoupled Kalman filter.

3.4 Zero Order Filter

The smoothing equation for height is:

$$\hat{H}_n = \hat{H}_{n-1} + \alpha_n (H_m - \hat{H}_{n-1})$$

where the hat notation ($\wedge$) refers to smoothed values.

H_m is the measured height

α_n is the damping factor which is computed from:

$$\alpha_n = \frac{\hat{\sigma}_{H_{n-1}}^2}{\hat{\sigma}_{H_{n-1}}^2 + \sigma_{H_m}^2}$$

The new smoothed variance is given by:

$$\hat{\sigma}_{H_n}^2 = \alpha_n \; H_m^2$$

where $\sigma_{H_m}^2$ is the height measurement variance.

The filter is initiated with a single height measurement and its variance. The damping factor is limited to a minimum value. A value of 0.03 is arbitrarily chosen.

A change of behaviour is detected by a plot falling outside the track noise gate which is taken as the previous track smoothed error plus the measurement error:

$$J^2 = \frac{\left(H_m - \hat{H}_{n-1}\right)^2}{\left(\hat{\sigma}_{H_{n-1}}^2 + \sigma_{H_m}^2\right)}$$

A track is deemed to have undergone a behaviour change if $J^2 > 4$ i.e. the two-standard deviation limit is chosen which gives an average false manoeuvre indication of 4.5%.

3.5 First Order Filter

The height and height velocity smoothing equations are:

$$\hat{H}_n = H_n' + \alpha_n (H_m - H_n')$$

$$\hat{\dot{H}}_n = \hat{\dot{H}}_{n-1} + \frac{\beta_n}{\tau} (H_m - H_n')$$

where $\alpha_n = \dfrac{a_n'}{\left(a_n' + \sigma_{H_m}^2\right)}$ $\qquad \dfrac{\beta_n}{\tau} = \dfrac{b_n'}{\left(a_n' + \sigma_{H_m}^2\right)}$

$$H_n' = \hat{H}_{n-1} + \hat{\dot{H}}_{n-1} \tau$$

$$a_n' = \hat{a}_{n-1} + 2\hat{b}_{n-1}\tau + \hat{d}_{n-1}\tau^2$$

$$b_n' = \hat{b}_{n-1} + \hat{d}_{n-1}\tau$$

a_n - height variance

b_n - height/height velocity covariance

d_n - height velocity variance

the smoothed variances components are:

$$\hat{a}_n = \alpha_n \sigma_{H_m}^2$$

$$\hat{b}_n = \frac{\beta_n}{\tau} \sigma_{H_m}^2$$

$$\hat{d}_n = \hat{d}_{n-1} - \frac{\beta_n}{\tau} b_n'$$

The filter is initiated having received two plots.

$$\hat{H}_2 = H_2 \quad \text{(measured)}$$

$$\hat{\dot{H}}_2 = (H_2 - H_1)/(t_2 - t_1)$$

$$\hat{a}_2 = \sigma_{H_2}^2, \quad \hat{b}_2 = \sigma_{H_2}^2/(t_2-t_1), \quad \hat{d}_2 = \frac{\left(\sigma_{H_2}^2 + \sigma_{H_1}^2\right)}{(t_2 - t_1)^2}$$

As in the zero order filter, the damping factors are limited by the use of plant noise. This can be thought of as the variances being limited by such physical effects as air turbulence. If the forecast variance falls to less than the 'roughness of flight factor' then the forecast position and velocity variance take on the following minimum values:

$$Q_a = 0.01\,\sigma_{H_m}^2 \quad , \quad Q_d = \frac{2Q_a}{\tau^2}$$

The manoeuvre check is similar to the zero order filter check and a two-standard deviation gate can again be used ($J^2 \geq 4$)

$$J^2 = \frac{(H_m - H_n')^2}{\left(\sigma_{H_m}^2 + a_n'\right)}$$

For a positive manoeuvre indication the forecast variances are incremented by the following quantities:

$$a_n' = q_n' + Q_a$$

$$b_n' = b_n' + Q_b$$

$$d_n' = d_n' + Q_d$$

$$Q_a = r^2/3 \quad , \quad Q_b = 2Q_a/\tau \quad , \quad Q_d = 2Q_b/\tau$$

The parameter r represents the maximum manoeuvre capability (in height) of the aircraft being tracked and will be a function of time since last up-date, plan speed and aircraft turn capability.

The filter damping factors are then computed as previously and if $\beta > 1$ it is limited to unity. The smoothed variances are computed as previously except the velocity variance which takes on the following value:

$$\hat{d}_n = \hat{d}_{n-1}$$

The change from first order to zero order filtering is not such a simple test as the reverse transition and will generally be associated with a first order manoeuvre indication. The test that has been evaluated is that the rate-of-height change should be within 0.5 standard deviations of height velocity error, on two consecutive occasions. This is not an optimised test but has been shown to work satisfactorily.

3.6 Effect of Height Accuracy on Projected Range Variance

The project range error will depend on whether the height is determined from an elevation measurement or is the default height discussed earlier. The mono-radar tracking system was the along and across the line of sight system (MORLEY, A.R. and WILSDON A.S. 1977) and the errors in these two dimensions are discussed separately. The across line of sight variance VX1 is assumed to be largely independent of range variance, even in the projected plan.

$$VX1 = D_o^2 \; Q^2 \; \sigma_\theta^2$$

In this case the height error will not affect VX1.

The projected ground plane used in the simulation was the orthographic projection with its tangency point at the radar. The conversion from slant plane to orthographic plane is given by:

$$D_o = Q \, D_{sl}$$

$$\text{where} \quad Q = \frac{(2R + H)}{2(R + H)} \left[\left(1 - \frac{H^2}{D_{sl}^2}\right) \left(1 - \frac{D_{sl}^2}{(2R + H)^2}\right) \right]^{\frac{1}{2}}$$

An approximation to Q used in the variance calculations is:

$$Q = 1 - \tfrac{1}{2}(\zeta + \eta)^2$$

$$\text{where} \quad \zeta = \frac{H}{D_{sl}}, \quad \eta = \frac{D_{sl}}{2R}$$

The projected-along-the-line-of-sight variance (i.e. the orthographic range variance) VY is approximated by:

$$VY = \sigma_{D_{sl}}^2 (Q + J)^2 + \sigma_H^2 K^2$$

$$\text{where} \quad J = \zeta^2 + \eta^2, \quad K = (\zeta + \eta)$$

The along sight variance can therefore be considered as being made up of two components, that due to the range error VY1 only and that due to the height error VY2 only, $VY1 = \sigma_{D_{sl}}^2 (Q+J)^2$ $VY2 = \sigma_H^2 K^2$

Figure 5 shows the variation of the projected range variances normalised with respect to $\sqrt{VY1}$, as a function of slant range. The height at each range was chosen as the default height and the two cases of no height measurement and the default height being the measured height are both shown. This figure demonstrates the large degradation of projected range error when height is not available, particularly at low to medium ranges.

The parameters used in the calculation were:

$$\sigma_{D_{sl}} = 200\text{m r.m.s.}$$

$$\sigma_{elevation} = 0.25^{o} \text{ r.m.s.}$$

$$\sigma_\theta = 0.2^{o} \text{ r.m.s.}$$

In the case of no height information the mono-radar tracking would be performed in the slant plane even though it is not a flat plane and anomalous accelerations are experienced, particularly for high-speed aircraft flying tangentially close to the radar. However, the transformation is necessary for multi-radar tracking where the local radar orthographic plane parameters are required for conversion to the system orthographic plane.

3.7 Summary

This section has presented a technique for determining an optimum height in the absence of height information. It details a height filter which has two modes of operation. Finally the effect of using the default height on the projected orthographic range is shown compared with the situation of a height measurement being available.

4. UNCOUPLED KALMAN FILTER

4.1 Introduction

An important decision has to be made in multi-radar filtering as to whether the Kalman filter should be implemented in its coupled or uncoupled form. The significance of uncoupling is there is at least a 50% saving on filter coding and run time. However, information is being rejected by uncoupling and this can have a significant effect on the tracking performance.

MORLEY, A.R. and WILSDON A.S. 1977 gave brief details of a method which was developed to investigate changes in tracking performance caused by decoupling. The method was based on determining the areas of the constant probability contour ellipses representing the errors of a particular position. In general, the error ellipse of a

position measurement will be aligned to the range vector. The position covariance terms in the Kalman filter account for the ellipse orientation. The uncoupling of the filter causes the covariance terms to be ignored. The error ellipse can only be orientated with respect to the x-y co-ordinate axes, and a different ellipse area will result. The parameter investigated was the area ratio of ellipses for the two situations after combining measurements from two non-collocated radars.

4.2 Tracking Performance

Figure 6 shows the constant area ratio contours for two radars separated by 2° latitude. The tracking performance of aircraft in the high area ratio regions was shown to be considerably degraded by decoupling the Kalman filter with average position degradation of 100% and speed and heading degradation of 60%.

Under manoeuvring conditions, the tracking performance was very little changed but this was the result of adding a manoeuvre matrix onto the forecast covariance matrix, which assumed circular errors and dominated the behaviour. However, in general, aircraft can manoeuvre greater distances in the across-track direction than in the along-track direction so that in the case of the coupled Kalman filter the maximum manoeuvre capability can be approximated by an ellipse aligned to the track-heading direction.

If V and U are the along and across track co-ordinates then the manoeuvre matrix covariance Q describing the state vector $\underline{Z}$ is

$$\begin{bmatrix} \sigma_U^2 & 2\sigma_U^2/\tau & 0 & 0 \\ 2\sigma_U^2/\tau & 4\sigma_U^2/\tau^2 & 0 & 0 \\ 0 & 0 & \sigma_V^2 & 2\sigma_V^2/\tau \\ 0 & 0 & 2\sigma_V^2/\tau & 4\sigma_V^2/\tau^2 \end{bmatrix}$$

where

$$\underline{Z} = \begin{bmatrix} U \\ \dot{U} \\ V \\ \dot{V} \end{bmatrix}$$

If a and b are the maximum manoeuvre distance in the U and V directions and all manoeuvre distances are equally probable then:

$$\sigma_V^2 = b^2/3 \quad , \quad \sigma_U^2 = a^2/3$$

It is necessary to rotate the covariance matrix through the heading θ before addition to the forecast covariance matrix.

The above analysis was performed for aircraft manoeuvring in the high area ration regions which gave a 20% improvement in track heading. The positions were very little changed and the speeds were actually degraded. The latter effect was solved by performing an additional speed smoothing with a small damping factor (0.1) such that the heading remained unchanged.

4.3 Lack of height case

The coupled Kalman filter also has an advantage in the case of the absence of height information at short to medium ranges. The most rigorous approach would be to include height and its first derivative as additional elements in the Kalman filter state vector. However, the additional computer loading is considerable and height is therefore generally filtered independently from the plan parameter. In the latter case there is still an advantage to implement the coupled Kalman because the azimuth errors do not become corrupted by the large height error affecting the projected range error.

4.4 Discussion

Whether or not the Kalman filter is implemented in its coupled or uncoupled form depends largely on the requirement of a particular system and the weighting factors of a trade-off analysis. When computer loading does not present a limitation, implementation of the coupled Kalman filter can result in a significant improvement of tracking performance.

5. SUMMARY

(a) It has been shown that a group of aircraft can be tracked automatically as a single entity after the manual designation of a four-sided boundary.

(b) A simple height filtering algorithm has been proposed which operates in either a zero-order or first-order mode. The effect of no height information has been investigated in terms of the errors on the projected range.

(c) Evidence has been presented to assist in the trade-off of implementing an uncoupled Kalman filter and the associated degradation of performance.

REFERENCE

MORLEY, A.R. and WILSDON, A.S., 1977 'Multi-radar Tracking in a Multi-site Environment', Radar 77, I.E.E. Conference Publication No.155.

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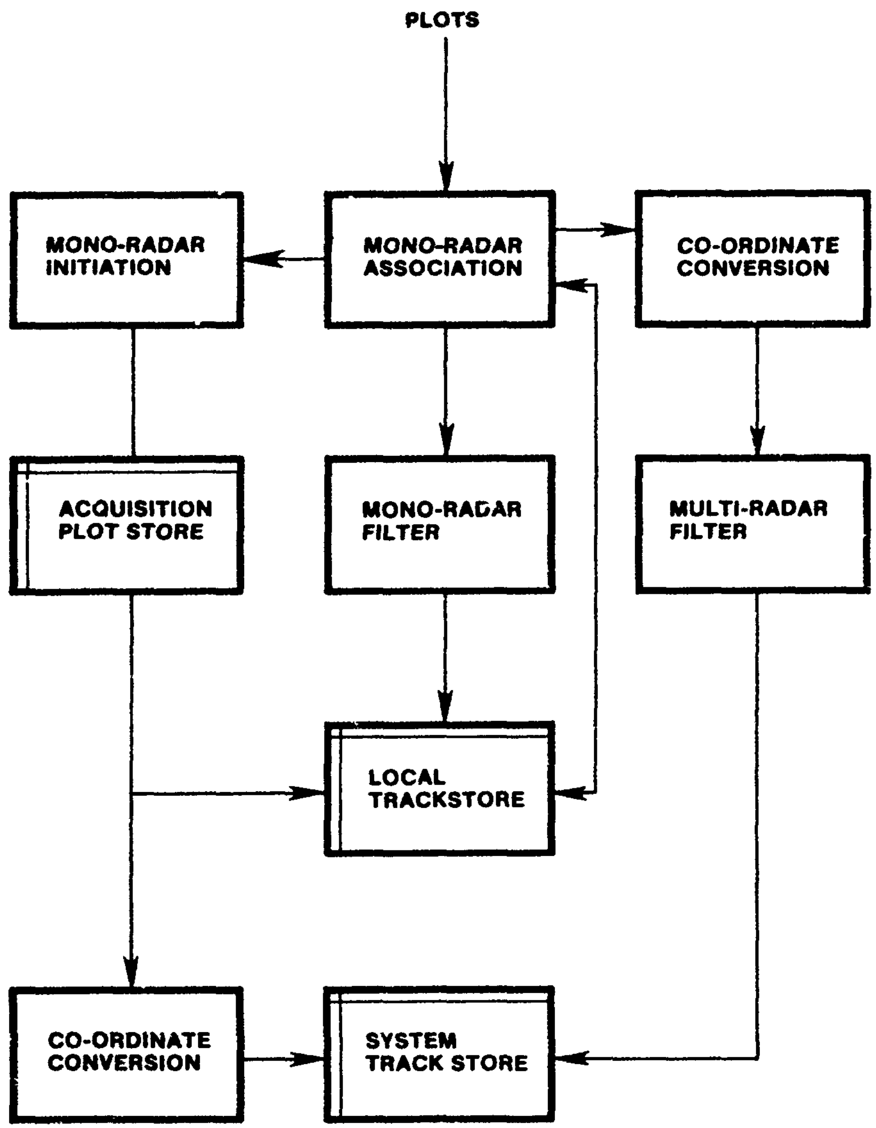

Fig.1(a) Distributed method

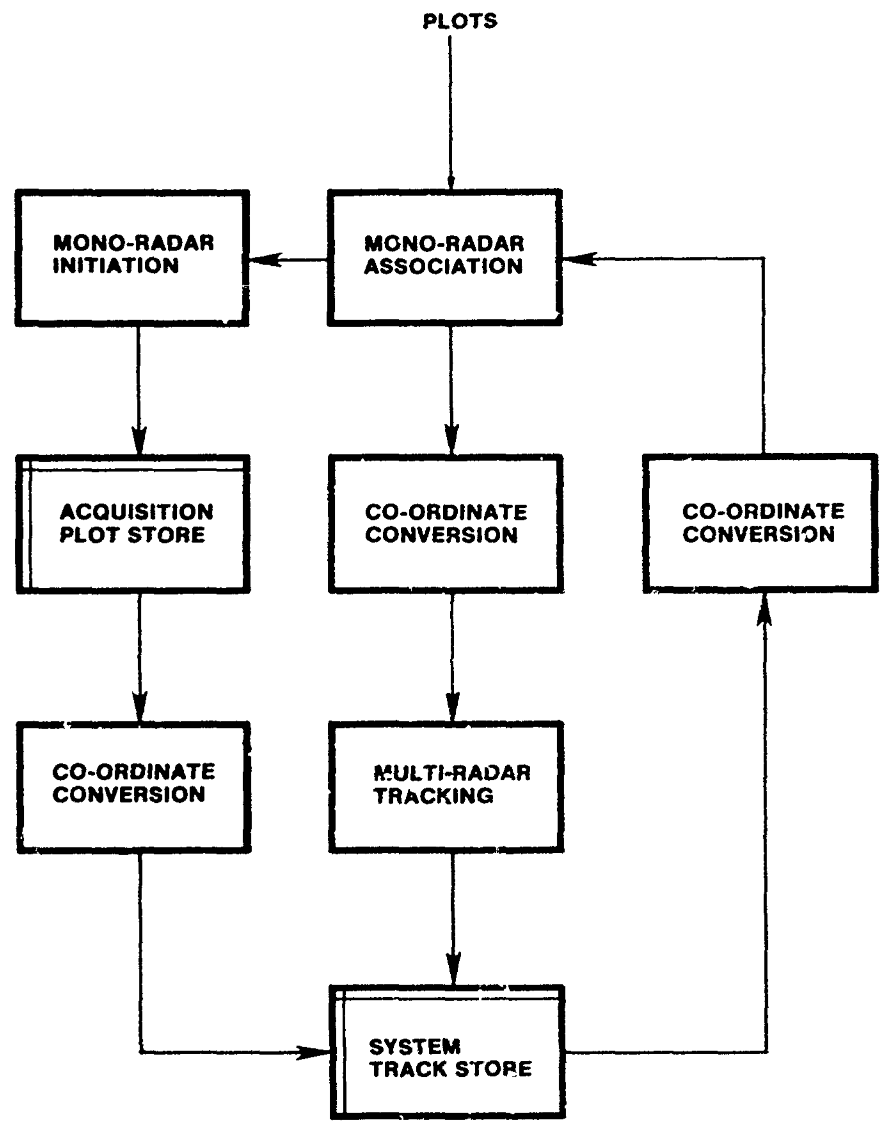

Fig.1(b) Integrated method

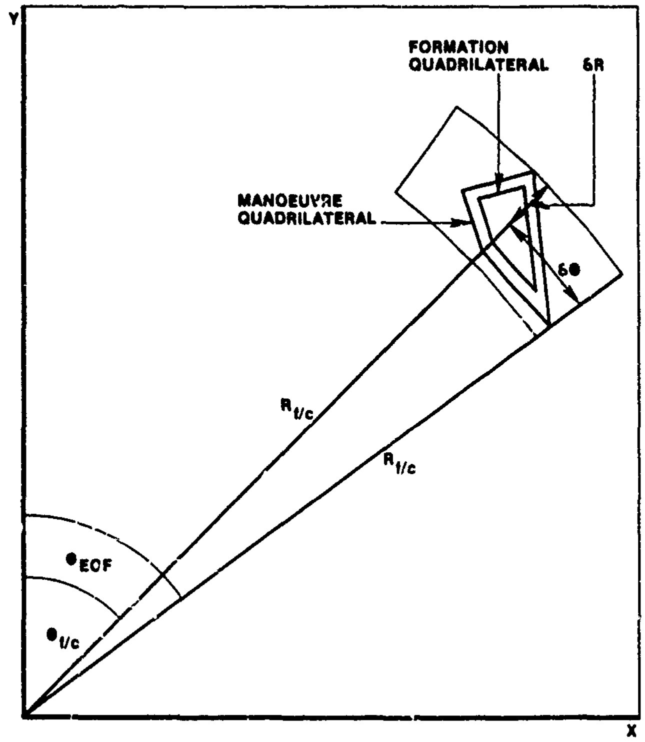

Fig.2 Formation association details

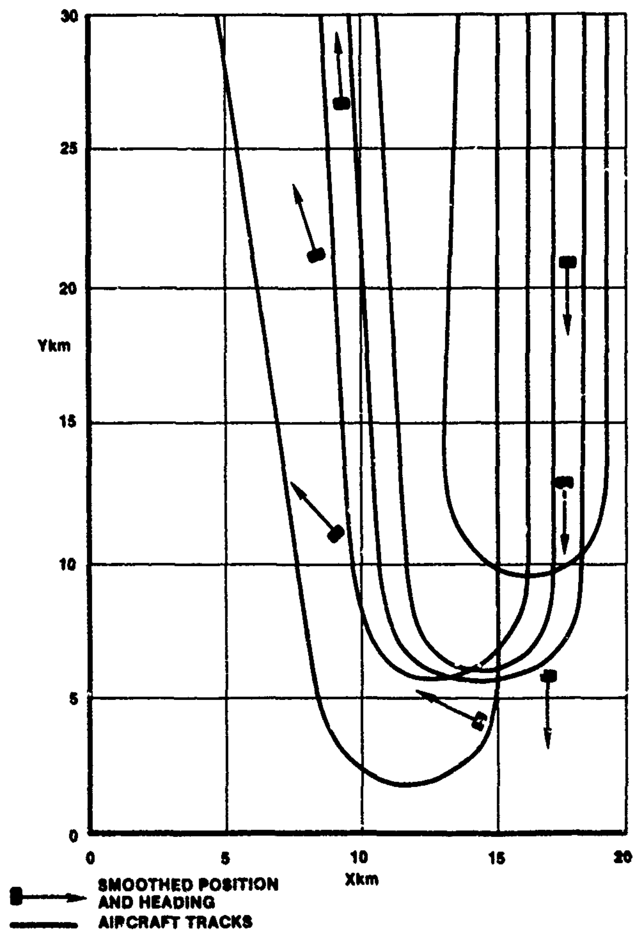

Fig.3 Formation manoeuvre

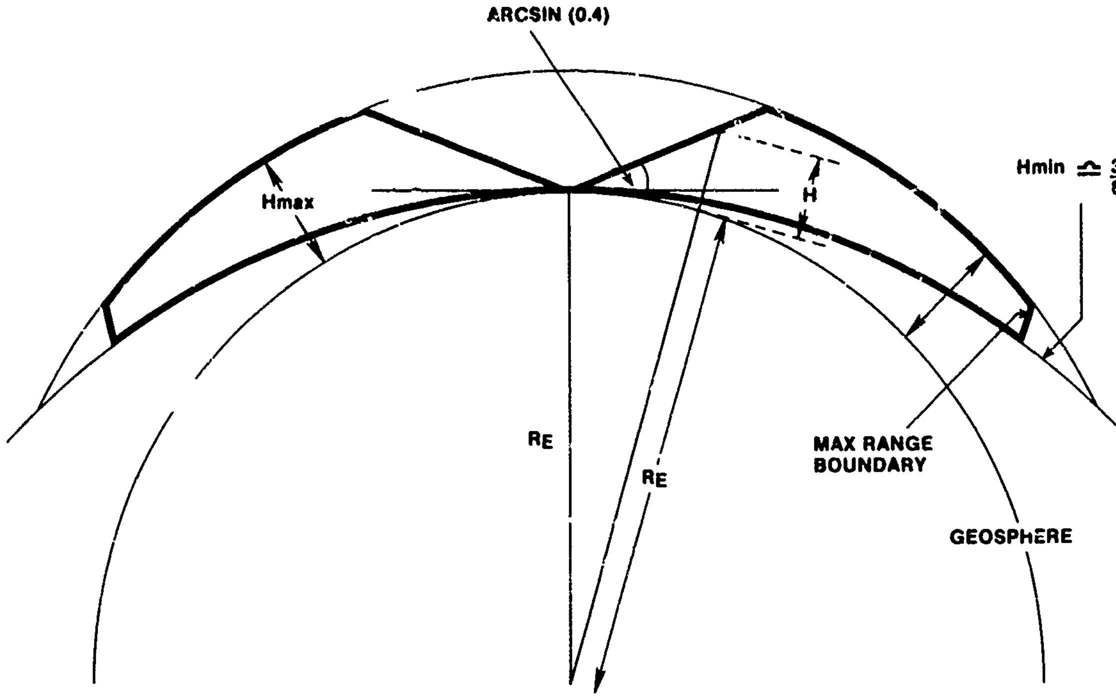

Fig.4 Section of height boundaries

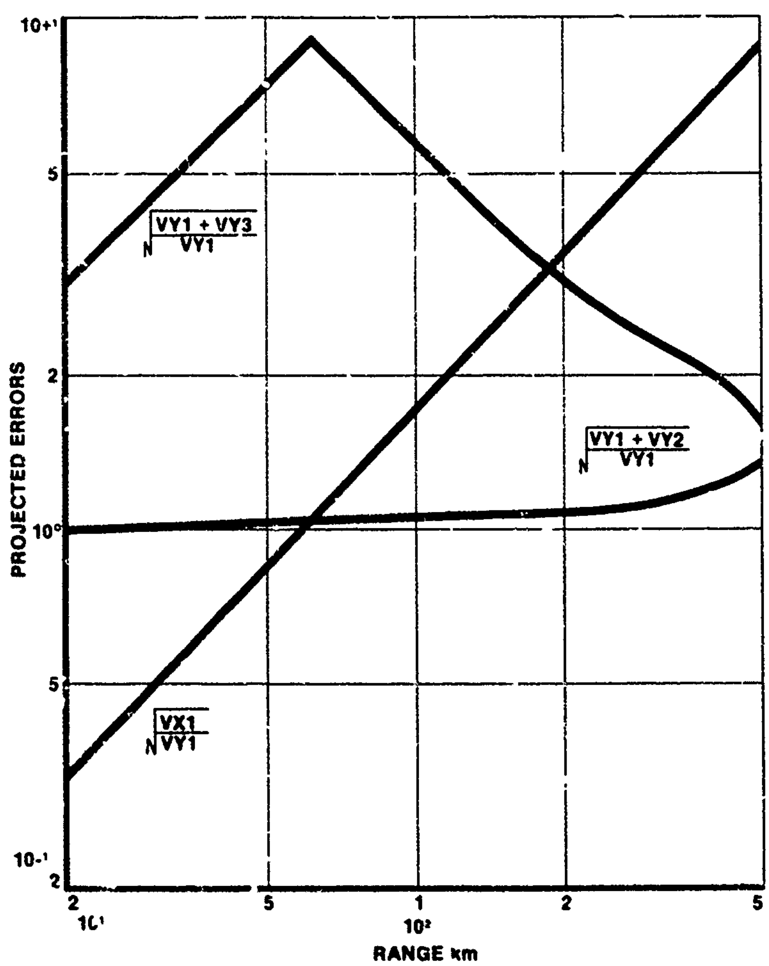

Fig.5 Projected errors

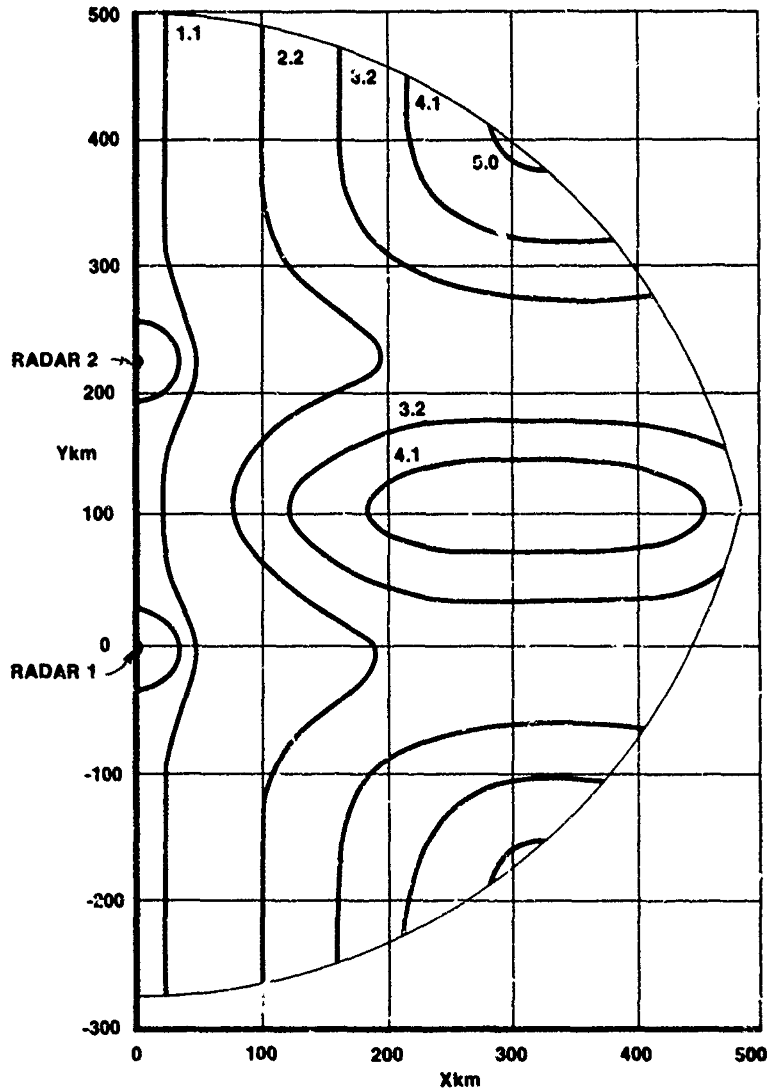

Fig.6 Constant area ratio contours

DISCUSSION

J.R.Moon, UK

You stated that work at Ferranti indicated that the tracking accuracy was far more sensitive to the choice of turn-detection algorithm than whether the filter was decoupled or not when tracking with a single radar. Are your conclusions dependent on the number of radars in the system?

Author's Reply

The area ratio analysis which I have discussed was also carried out for a single radar and showed that the effect of decoupling the Kalman Filter was not critical. I would expect that for more than two radars, again, the effect would not be critical. However, the effect is dependent on the relative accuracy of the range and bearing errors and at large range the decoupling effect could be more dramatic for widely differing errors.

ALGORITHMS FOR SIMULTANEOUS AUTOMATIC TRACK INITIATION IN MULTIPLE RADAR NETWORKS

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SUMMARY

In multiple radar networks where the distribution of radar stations is dense with respect to the individual areas of coverage, an incoming target may often be detected by several radar sensors almost simultaneously. When the tracking facilities of the network are autonomous and decentralized while the useful capacity of the processors and of the data channels between the stations is severely limited, track initiation and management cannot be performed effectively by conventional methods.

The system considered in the paper uses tracking facilities of equal authority collocated at every radar station. Redundant communication links between the stations provide a failure tolerant data exchange capability. The paper describes the algorithms leading to a unique system track for a target entered into the system by several radar sensors while each of the collocated tracking facilities starts an individual track by pooling radar information from its own sensor and from neighbouring sensors seeing the same target. The functions of automatic multiradar track initiation and management for echo targets are illustrated by some simulation results. Extension of the algorithms to ... e tracking and triangulation is outlined at the end of the paper.

1. INTRODUCTION

Radar- and track-data processing is developed for application in a multiple radar network with overlapping radar coverage (Fig. 1). All radar stations are interconnected by uni- or bidirectional data links (Fig. 2).

The surveillance system has to cope with more than 100 targets of unknown identity, flying in the system surveillance coverage. Most of the targets are assumed to manoeuver extremely at very low altitudes. Aircraft at higher altitude are assumed to fly at maximum velocity (Fig. 3).

Tracking algorithms provide a unique track with an unambiguous track number at all stations for each target entering the system surveillance coverage even if it is detected by several radars simultaneously. The system track number is kept unambiguous even if target trajectories are crossing. Tracking of targets flying in formation is limited only by the resolution capabilities of the radars.

Consideration is also given to tracking of jammers by triangulation of jammer bearings measured by several radars.

2. SYSTEM DESIGN

The most important components of the radar surveillance network are (Fig. 4)

- Radar sensors with data extractors
- Data links (including receiver and transmitter equipment)
- Track data computers
- Coding/Decoding Equipment

2.1 Radar Stations

The radar stations have to accomplish

- t[illegible]t detection
- d[illegible] extraction
- dat. correlation
- track computation
- data distribution and
- display of air situation

According to these tasks each station is equipped with (Fig. 4)

- one radar out of various types
- one track data computer (TDC)
- several receivers
- one transmitter and
- a display unit

To detect all targets, in low level flight and in the upper airspace, different types of radars with different performances are interconnected by digital data links with medium rate transmission capacity (Fig. 5).

Use of several receivers per station permits a meshed data link network and allows for multiple redundant data transmission. On the other hand redundant data distribution causes a large amount of data feedbacks which are to be eliminated by each track data computer. Furthermore, a timing procedure for data distribution is necessary to assure, that track data of each track are distributed at nearly an equal rate (see chapter 4). To recognize transmission errors, and to correct them, track information is channel coded.

To accomplish distributed track data processing, the TDC has to meet the following requirements:

- Fixed and floating point arithmetic
- 16 bit word length
- Internal memory 128 K Byte, with provision for expansion of memory
- Directly addressable 64 K Byte
- No auxiliary storage
- Sufficient number of 16-bit registers
- Operating speed of approximately 200,000 operations/sec.
- Stored program: The operating system needs about 30 K Byte, the user program up to 80 K Byte and more, depending on the jammer tracking capabilities
- Program language: high level language for algorithms, assembler for I/O-procedures.

2.2 System Operation

The radar network consists of 10 to 20 mobile radar stations with overlapping radar coverages to attain a good system detection probability for extremely low flying aircraft at terrain following flight profiles (Fig. 6). The radar/tracking stations are mobile, both 2-D and 3-D radars. Their variable positions will be primarily chosen with the aim of optimal radar coverage of the entire network with special regard to the lowest level flight profiles /1/.

Data communication is realised by transmitting track data omnidirectional to every other radar station within radio range. Depending on the number of its receivers, each station is able to receive track data from several stations. Mostly, data links between two stations are bidirectional. A unidirectional data link is given, if in one of two communicating stations all operational receivers are tuned to other stations or if radio disturbances of the received frequency are present. The design of the algorithms for track initiation and tracking avoids a central track management. Consequently, since the network needs no central processing station, a wide range of possible system configurations can be handled. In general a fully mesh-operated network will be installed (Fig. 2). On the other hand no operational constraints during build up, change or decomposition of the tracking network are imposed. Net splitting and reformation, or connection of additional compatible networks are practicable during system operation and do not cause any restrictions such as a new system initiation.

If jammer tracking is initialized, high priority is provided to jammer data processing and display.

2.3 System Output

Computed track information is transmitted and simultaneously displayed on a digital display unit. This information is to be updated in less than or equal to 4 seconds. This enables the operator to check tracking results and, on demand, to classify the type of target (friend, unknown, mass approach, jammer).

Transmitted and displayed information from and at every radar/tracking station has to reflect the same air situation. Therefore, users of the track information may connect themselves to that radar/tracking station which is most convenient to them.

Due to the requirement of target allocation to weapon systems, tracks must have maximum life time and minimum data aging.

3. TRACKING ALGORITHMS

Tracking is realised simultaneously in each radar station, even if its own radar does not detect the target. If a new target is detected, stations obtaining the corresponding data form a preliminary track and distribute track information to all other sta-

tions. They correlate all gathered information and join it to a common system track with a unique track number. Track initiation is finished after a fixed time period which is large enough to ensure that all stations know the system track number.

3.1 Plot Data Processing

Every target detection by radar is reported to the Track-Data-Computer (TDC) of the radar station which tries to associate the target report to a suitable existing track (Fig. 7). For positive association, it is necessary that the reported target is positioned within the expected window of the predicted registered track. Type of target information is not used as an association criterion, for reason of its small reliability /2/, /3/.

If there is no association possible between the reported radar plot and and any registered target track, the TDC tries to initiate a new track. It stores the reported plot data into a System Track Memory (STM) as a potential track (Fig. 8) for possible association with track data expected during the next rotation of the radar antenna. In absence of an expected second plot report, the potential track is assumed to be a false target report, and its data in the STM will be cancelled. (If the radars used have a small detection probability, a third antenna rotation can be tolerated for a second detection of the target.) If the radar does report a suitable plot in the next antenna period, both plots will be joined to a preliminary track and a track message is externally distributed for the first time. For each association check, the plot data derived from a 2D-radar will be slant range corrected. Slant range error is the difference between the measured slant range to the target and the lenght of the line of sight projection on to that horizontal plane, which contains the radar's position (Fig. 9). At large elevation angles, the slant range error may amount to 30 % of the slant range. In lack of height information, measured slant range must be interpreted as the horizontal range. This may result in shifts of the computed target position and in bendings of the track. If the slant range error is large enough to affect association, a new track will be initiated, so that the same target is tracked twice.

For slant range correction, height information from any 3D-radar or SSR-information can be used.

3.2 Track Data Processing

Each station, which receives a track message checks whether that track is associable to a track, which is already registered in its own STM (Fig. 10). First it looks for the reported track number. If the station finds it in its TDM, it checks whether the reported target fits to the registered track. If the station cannot find the same track number in its STM, or if there is no correlation between the tracks with the same track number, it checks all registered tracks to correlate the received track information with the most suitable track. To enhance the survivability of final tracks, they are preferred to preliminary tracks for association. If there is no correlation even to a preliminary track the received track message is added to the other registered tracks and forwarded per data link to all neighbouring stations. In case of an association of two tracks with different track numbers, a track number harmonization procedure provides an unambiguous final track number in all stations.

Associated track data will be used to update the appropriate track, provided that the received target information is more actual than the last registered track information. Older messages will be disregarded. After updating, a track message containing the most actual track data is cleared and transmitted to neighbouring stations in accordance with the track reporting procedure (see chapter 4).

Tracks will be carried on in all stations as long as the target is detected by at least one radar. After a target has been missed for a fixed time period the track is terminated (see Fig. 8). This time period is determined by the slowest antenna turn rate among the radars used, in order to give the TDC a chance to continue tracking in spite of missing a target in one antenna period. There is no sense in waiting longer for a radar plot because prediction quality decreases rapidly and the track-window for the expected plot position would have to be enlarged accordingly. Furthermore, in a dense air situation the probability of false association of other targets increases simultaneously.

3.3 Data Filtering

Target data delivered by radar and those which have been received from neighboring stations via data link have quite different character. Radar derived data are most actual but contain less information (Fig. 12) and are less reliable than track messages which have been filtered once. To evaluate both kinds of information in an optimum way, two separate filters are employed (Fig. 11).

Radar derived data are, at first, associated with a suitable sensor track. Sensor tracks contain exclusively information from the radar of its own station. The ensemble of sensor tracks of one station constitutes the so called sensor derived air situation of this station.

Sensor track data contain the same amount of information as track messages. The next step is to update the appropriate system track. The ensemble of system tracks constitutes the system derived air situation which includes every target detected from any radar of the system. All track data of the system derived air situation are stored in the STM for updating and distribution according to the reporting procedure (see chapter 4). There are many advantages in filtering radar-derived data separate from the other system track data received by data link /4/, /5/.

Firstly, all data derived from the own radar of the station have a constant systematical bias. By correlating only target data from the same station the bias has no effect on plot associations. This increases the probability of a correct association of successive target reports.

Secondly, the constant bias and the adequate sampling time of the radar antenna improve the computation of the target velocity. If track positions received by data link would be utilized for the velocity computation instead, two problems would arise:

- different biases of detecting radars would run up,

- by utilization of messages one shortly after the other (e. g. the first two track messages from channel 1 and channel 2 in Fig. 13), the radar measurement error can be of the same magnitude or greater than the distance the target has flown in the meantime.

Both problems result in an error of the computed target velocity followed probably by a wrong association.

Both advantages, i. e. correct associations coupled with improved velocity computations lead to a good smoothed track of high quality and high reliability.

The second filter correlates sensor track data, and system track data received via data link, with stored system track data to update the system track. This can be realized by Kalman-filtering or using an α/β-filter, perhaps with dynamic coefficients depending on track quality. Criteria for track quality can be:

- the lifetime of a track
- the track status (preliminary or final)
- the amount of associated and correlated target reports from the own radar of the station
- the amount of correlated track messages received by data link
- the time elapsed since the last updating.

3.4 Track Number Management

Track number management provides identical track numbers for every target track in each radar station. It is activated in two cases:

- For harmonizing different track numbers concerning the same preliminary track
- For rechanging final track numbers in a predefined way in all stations if numbers of different final tracks have been exchanged.

3.4.1 Harmonizing Preliminary Track Numbers

Due to the overlapping coverage, many incoming targets are initially detected by several radar sensors at almost the same time. Each radar station, which detects a target twice in subsequent detection cycles distributes a track message with a preliminary track number. Since each station has a specific prefixed pool of track numbers, preliminary track numbers assigned by different stations are always different, even if they apply to the same target.

If a station associates two tracks which are the same but have different preliminary track numbers, the track management elects the smaller number to survive. The track message which is forwarded on contains the most actual track data but the smaller track number.

Depending on the network constellation, a message needs a certain minimum time to reach all stations. For the harmonization of different track numbers related to the same target a period of twice of this time is sufficient (pre-phase period). At the end of this period each message concerning this particular target contains the unique final track number.

3.4.2 Rearranging Ambiguous Final Track Numbers

A puzzling situation arises in every tracking mechanism when targets fly crossing trajectories or when targets split up after flying in close formation. Consequently, track-numbers tend to be swapped (track A, number A and track B, number B change into track A, number B and track B, number A respectively), or track numbers are doubled (two tracks with the same number), or tracks will be doubled (one target, two tracks with two numbers).

To restore the unambiguity of final track numbers, each station induces a harmonizing track management procedure, which rearranges track numbers in a predetermined way.

If the radar accuracy is less than the separation of the targets, neither the radar data extractor nor a human operator can decide, which of the reported radar plots belongs to which target. In view of this fact, targets flying close together or flying crossing trajectories are tracked separately with different track numbers, but the unambiguity cannot be guaranteed. This lack is not critical for system operation, since the overriding point for distributed track data processing is, that all stations have the same number for a given track, even if targets are exchanged. Recognizing this, a very simple changing procedure is chosen to save computing time. Examples of simple changing criteria are as follows:

- the target flying the most southern track gets the smaller track number

- if both targets fly at the same latitude, the target which is flying the most western track gets the smaller track number.

4. DATA DISTRIBUTION

The TDC distinguishes (Fig. 12):

- Target reports from the radar of its own station
- Track messages containing a preliminary track number
- Track messages containing a final track number.

Target reports themselves will not be distributed externally but they trigger the distribution of track messages. Track messages containing a preliminary track number are distributed as quickly as possible to all radar stations of the network in order to shorten the preliminary tracking phase. To reduce the quantity of messages circulating in the network, a message received by a station is forwarded only, if the corresponding registered track is being updated or if its track number is being changed by that message. This way, feed back messages from the originating station are eliminated.

Regarding the data reduction task, we note that each station has n+1 data input channels (Fig. 4), but only one output channel with a capacity equal to the input channels. Therefore, on the average only the (n+1)th part of all reported messages can be relayed to the next station.

Since transmitting capacity is limited by the specified hardware and transmission procedure it is easy to calculate the available net message rate per target. For example, if the message rate is one per k seconds, only those messages are forwarded, that prolong a track by at least k seconds with respect to the last message. The new message transmitted contains the most actual smoothed track data.

To reduce aging of messages on their way through the network, radar returns get priority above messages received per data link in triggering new messages (Fig. 13). Fortunately, the turn rate of most of the radar antennas in the system is twice the message rate for each target. Consequently, each radar, which detects a target causes the station to trigger its message clearance at every other antenna rotation. So, aging of messages occurs almost exclusively at stations which do not see the target concerned. In case a target return is missed, the next available message - from radar or per data link - will trigger the transmission of the new message. Theoretically the maximum aging rate is k s per station, but in practice a slightly larger rate can be assumed.

5. SIMULATION RESULTS FOR ECHO TARGETS

Track initiation and maintenance has been simulated under a set of realistic assumptions in order to test the sensitivity of the above algorithms with respect to non-ideal situations.

5.1 Real Radar World

The tracking facilities discussed above must operate in an environment with a variety of interferences and non-ideal radar inputs /6/.

Interferences by terrain are:

- Blind sectors
- Shadow areas
- Ill-conditioned data transmission

Taking into account lower and lower levels of flight profiles, blind sectors and shadow areas in radar coverage expand rapidly (Fig. 14). Increasing undulation of terrain will adversely affect both radar coverage and data links.

The measurements of the radar sensor are contaminated by

- Radar noise
- Clutter
- Stochastic false or virtual echos
- Reduced detection probability
- Intelligent jammers

5.2 Effect of Failures

The following failures have been analysed with respect to their effect on system operation:

- Receiver failure
- Radar failure (relay function remaining)
- Total failure of radar/tracking station

5.3 Examples

The following examples show some results of simulating the algorithms for echo targets under the conditions given above.

5.3.1 Multisensor Tracking

Figure 15 shows the radar plots obtained by four radars looking at a simulated flight of three targets. Each radar/tracking station has to process all radar plots from its own radar and all track reports from the three other stations.

5.3.2 Crossing Trajectories

Figure 16 demonstrates tracking of two targets flying crossing trajectories at the same flight level. The first intersection is rectangular, the second one is at an angle of 45 degrees. Track numbers do not change after crossing. Due to a great number of simulated false radar echos, some isolated false preliminary tracks do appear but terminate after one report, with one exception which is reported twice (track number 2073).

5.3.3 Formation Flight

Figure 17 shows an air situation with three formation flights of four targets each. 15 radar/tracking stations are operative.

After a certain time at least three tracks are established for each formation. Since target discrimination by the radars differs from rotation to rotation updating time of the separate tracks varies.

6. STROBE TRACKING AND TRIANGULATION

Design of effective radar networks should take into account the possibility of jammer tracking by direction finding with several radars. The system described includes a strategy for automatic track initiation of strobe tracking and strobe triangulation. The procedure is applicable to stand-off jammers (SOJ) as well as to self screening jammers (SSJ) and escort jammers (ESJ).

6.1 Parameters

Important parameters which have a strong influence on the quality of the discussed triangulation and tracking method are

- Number of jammers a single radar is able to distinguish per antenna revolution
- Accuracy of bearing measurement
- Number of radars taking bearings of a distinct jammer
- Total number of interconnected radar stations
- Total number of jammers within system coverage
- Beam width of jammer (jammed angle)
- Jammer position relative to the surveillance area
- Jammer positions relative to one another

6.2 Method

The strategy of strobe tracking and jammer triangulation uses a decentralized procedure as in the case of echo target tracking.

The principle of strobe evaluation in each radar station is shown in Figure 18.

The electromagnetic emission of a jammer (SOJ, SSJ, ESJ type) is used by the passive detecting sensor to obtain bearing information of the target. After having initiated a station referenced bearing or strobe track in a given station, this track and the incoming strobe tracks from the neighbouring stations are triangulated, respectively. These correlations lead to individual jammer plots which are passed through a tracking filter logic in order to get jammer target tracks.

The appropriate track number management yielding system tracks is performed in a similar manner as in the case of echo target tracking.

The tracking filter for strobe evaluation can be of the same type as in the case of regular echo target tracking.

The problem of ghost targets resulting from the great number of possible points of intersections has to be minimized by

- chosing the appropriate number of intersections in a limited area yielding one target and by

- connecting the software modules "echo target tracking" and "strobe target tracking", respectively.

7. CONCLUSION

For multiple radar networks with overlapping coverage areas and decentralized tracking facilities, effective methods for simultaneous track initiation and management are of high importance. The algorithms outlined in the paper have been shown to operate with dissimilar radar sensors at mobile stations in all phases of system build up, reconfiguration and decomposition. Due to the inherent flexibility of the system architecture, tracking capability is tolerant with respect to sensor and communication degradation or failure.

Automatic track initiation is performed in three stages: potential track based solely on the first radar plots of the radar facility collocated with the tracking computer in question, preliminary track pooling information from the own and neighbouring sensors and final system track having a common unique track number in all stations of the system. Special harmonization procedures ensure track establishment and maintenance also in ambiguous air situations such as maneuvering targets, crossing trajectories and formation flights.

It has finally been shown that the algorithms for echo targets can be modified and extended to handle jammer targets as well.

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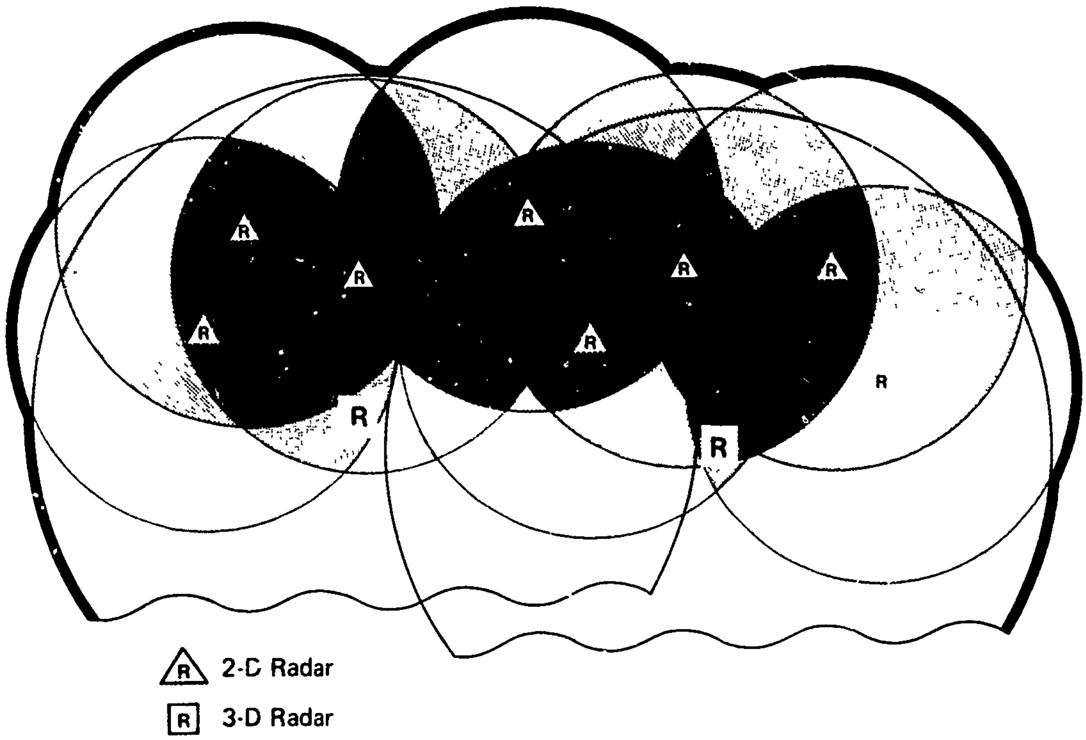


Fig. 1 System Surveillance Coverage

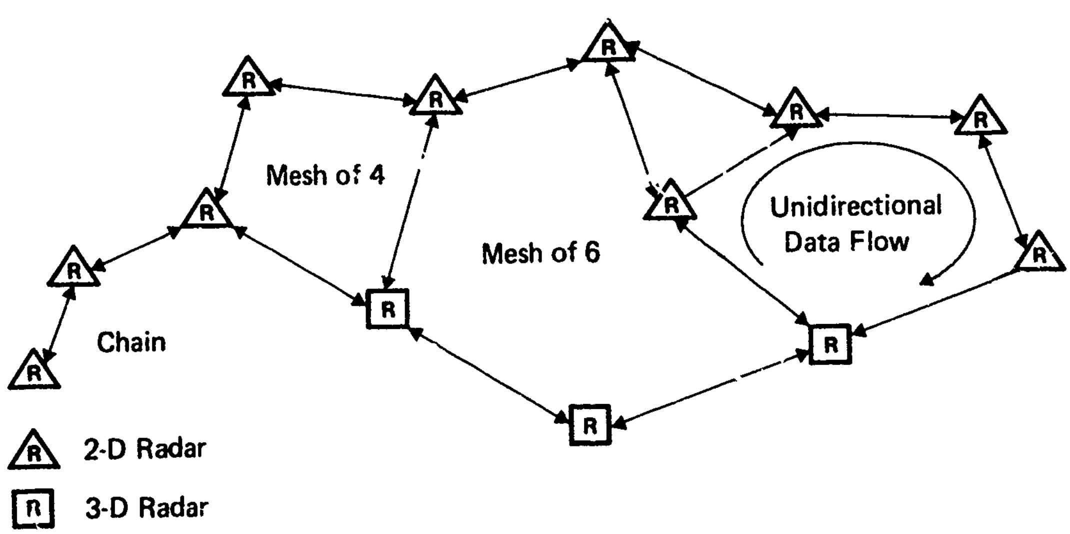


Fig. 2 Network Configuration

- More than 100 Targets
- Extreme Low Level Profiles
- Upper Flight Levels
- Highly Manoeuvering Targets
- Crossing Target Trajectories
- Formation Flights
- Jammers
- False Targets
- Clutter
- Disturbed Data Links

Fig. 3 Environment

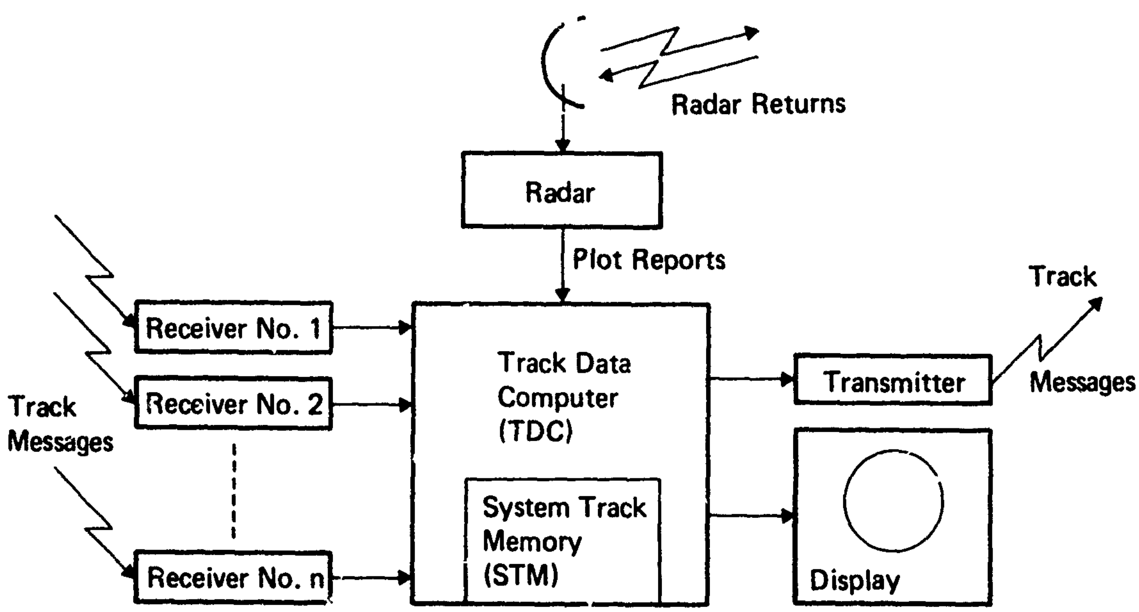


Fig. 4 Radar Station Configuration

- Mobile Radar Stations
- 10 to 20 Radars
- Various Types of Radars (2D, 3D, SSR)
- Different Radar Performances
- Track Data Computer at Each Station
- No Central Processing Station
- Medium Rate Digital Data Links
- Channel Coding for Data Protection

Fig. 5 System Architecture

- Overlapping Radar Coverages
- Meshed Network
- No Restrictions by Network Variations during Operation
- Multiple Data Redundancy
- Quick Data Distribution
- Most Actual Track Information at Each Station
- Unique System Track
- Unambiguous Track Numbers
- Equivalent Air Situation at Each Station
- Long Track Life (Time)
- Priority for Jammer Tracking

Fig. 6 Operational Requirements

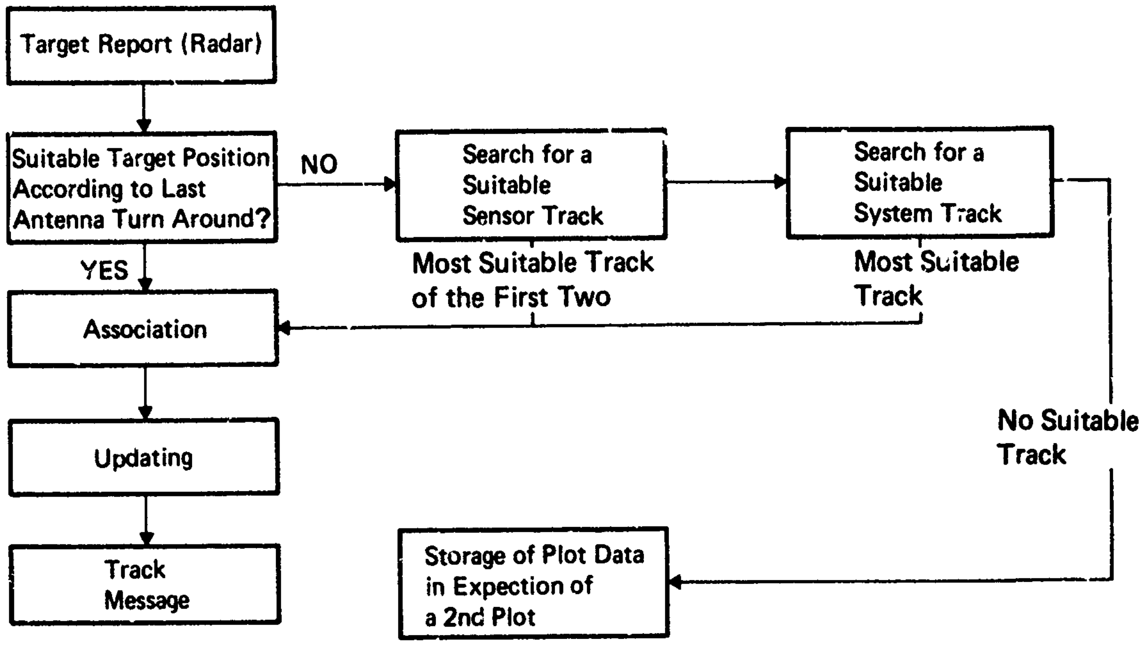


Fig. 7 Plot Data Processing

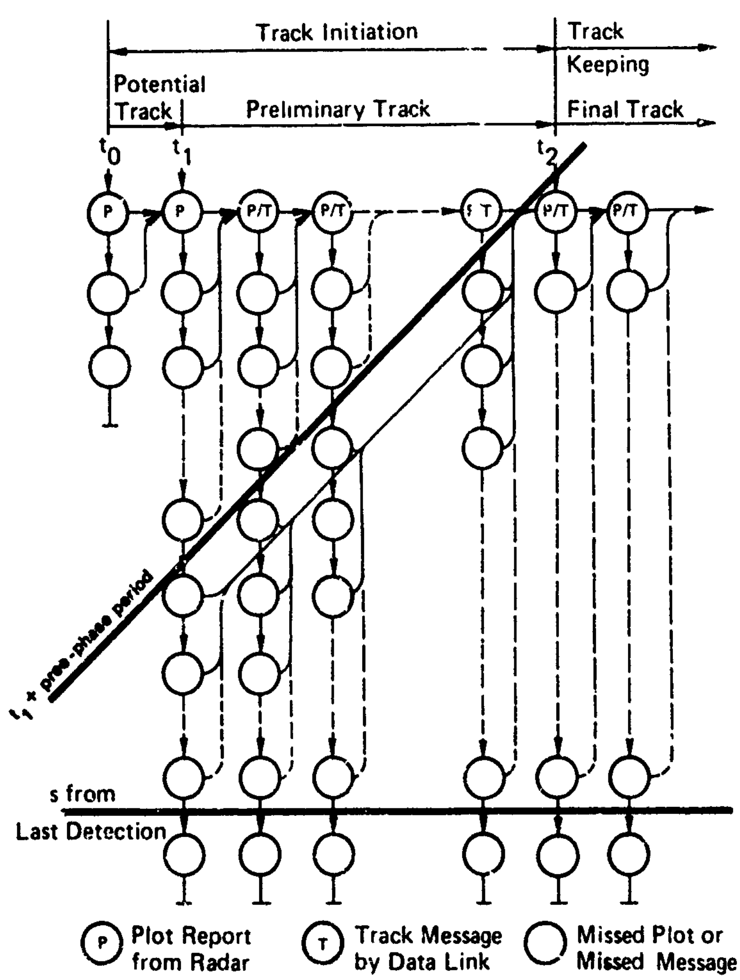


Fig. 8 Track Stages

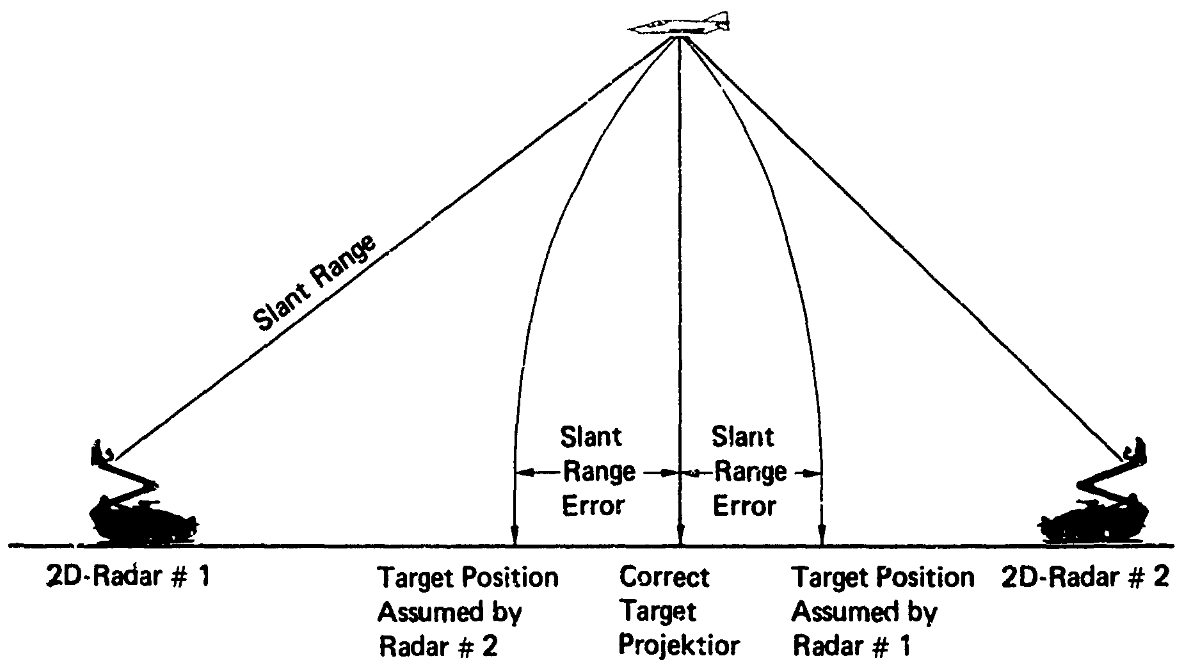


Fig. 9 Slant Range Problem

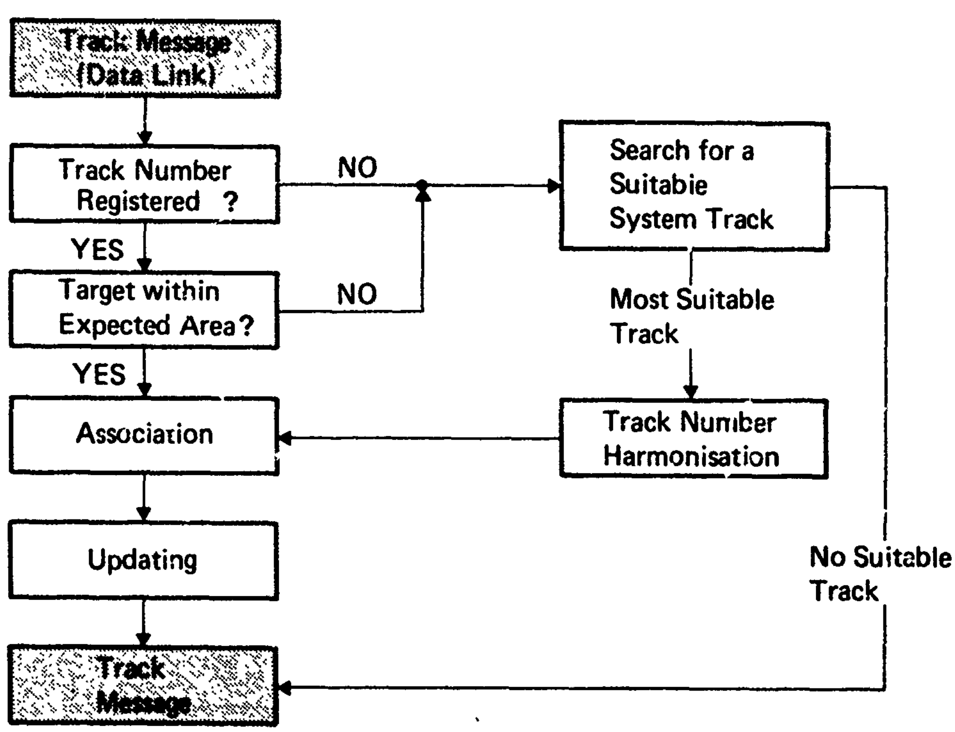


Fig. 10 Track Data Processing

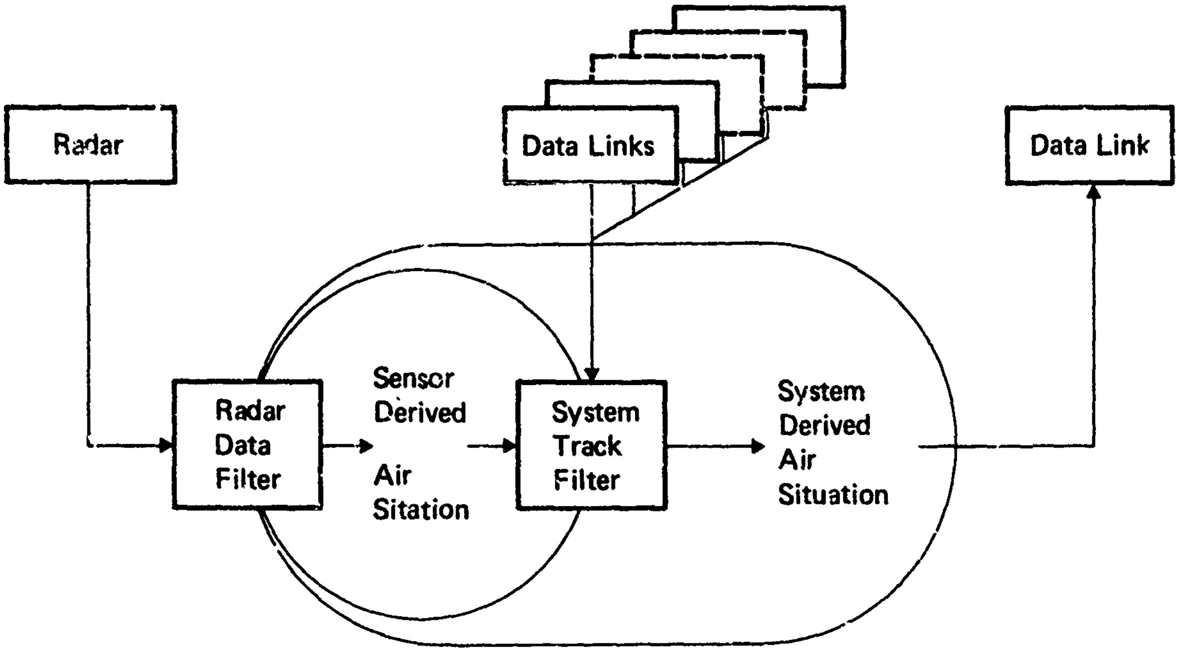


Fig. 11 Track Data Flow

TARGET REPORTS

- Target position
- Target Altitude, if Measured
- Date of Measurement
- Type of Target

TRACK MESSAGES

- Track Number (Preliminary or Final)
- Target Position
- Target Altitude, if Measured
- Target Velocity
- Date of Measurement
- Track Quality
- Type of Target

Fig. 12 Communication Contents

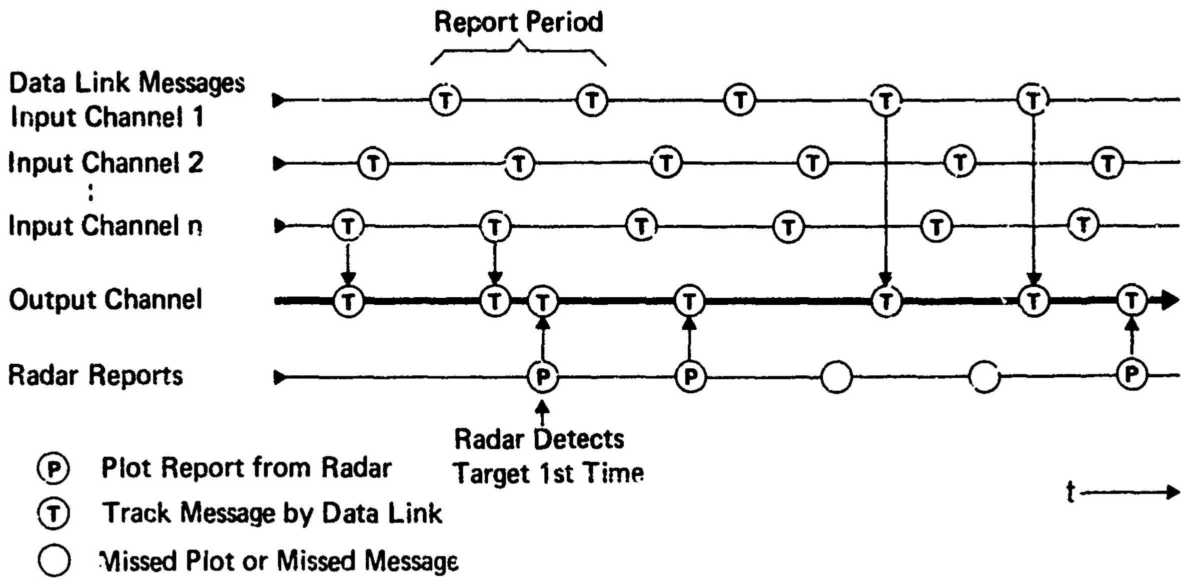


Fig. 13 Track Message Reporting Procedure

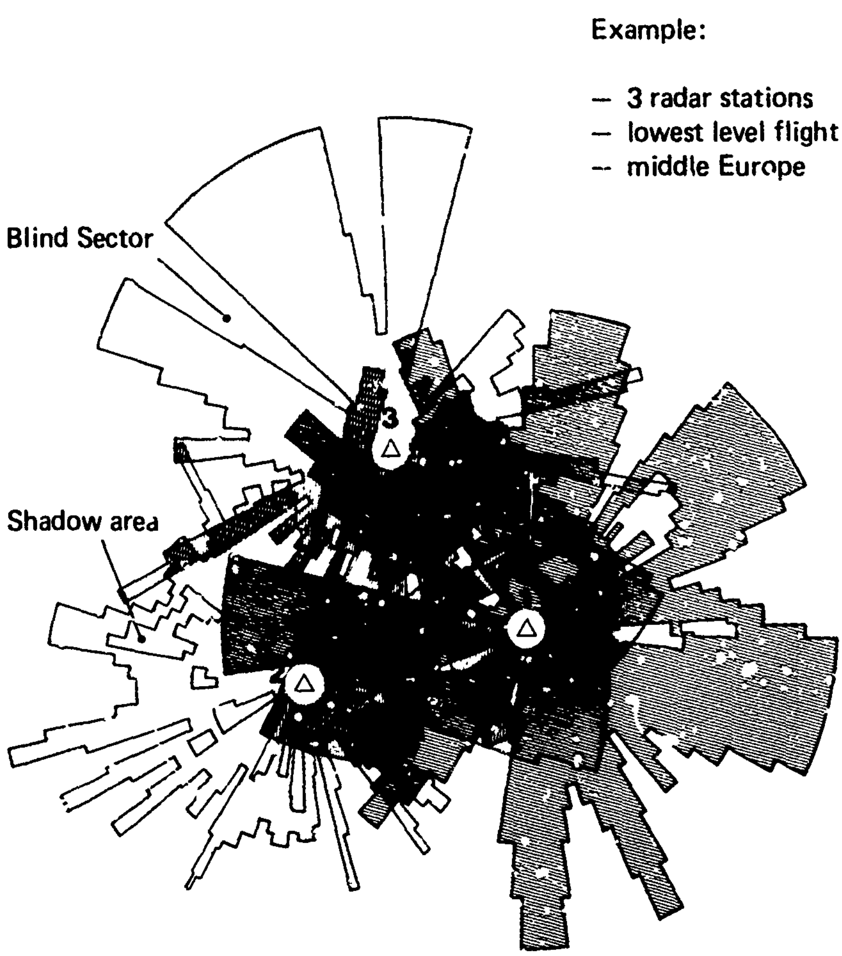
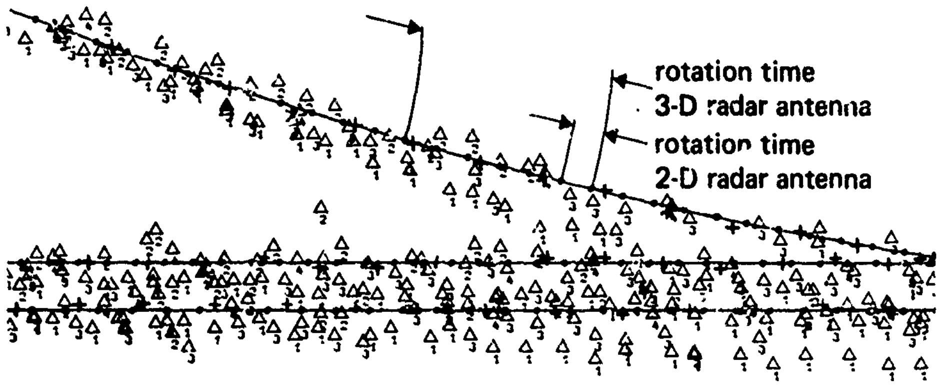


Fig. 14 Radar Coverage



Example:
Three targets
Three 2-D radars (1, 2, 3), one 3-D radar (4)

Δ_n Radar report from radar n

\+ Track report of radar 1

Fig. 15 Multisensor Tracking

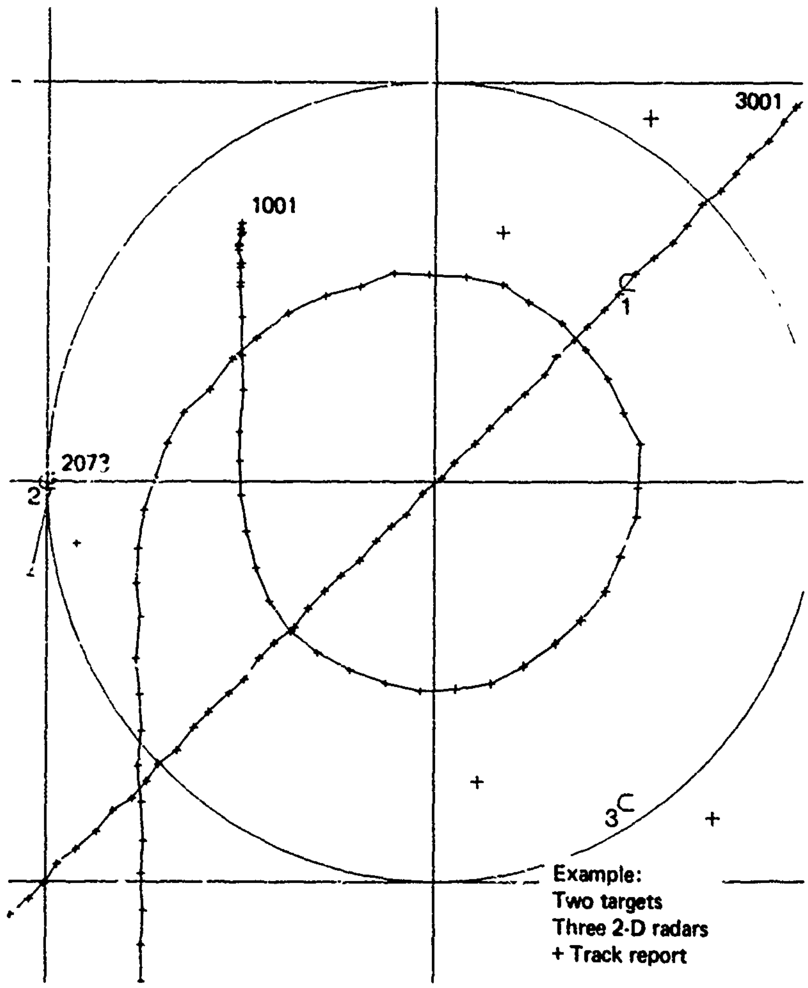


Fig. 16 Crossing Trajectories

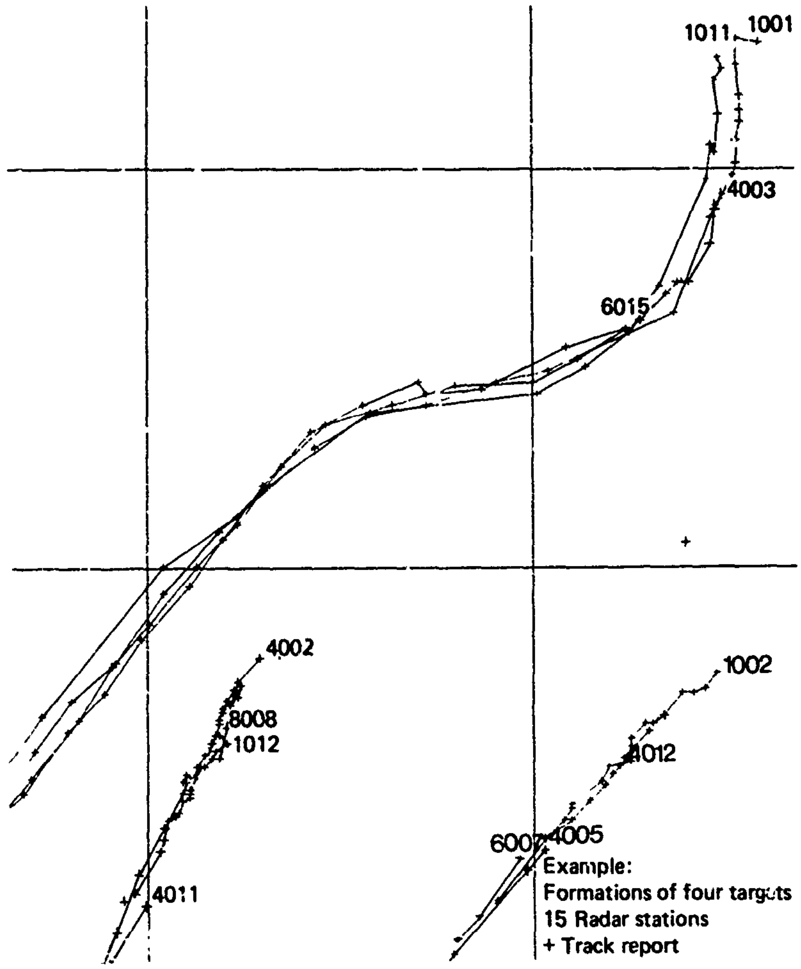


Fig. 17 Formation Flight

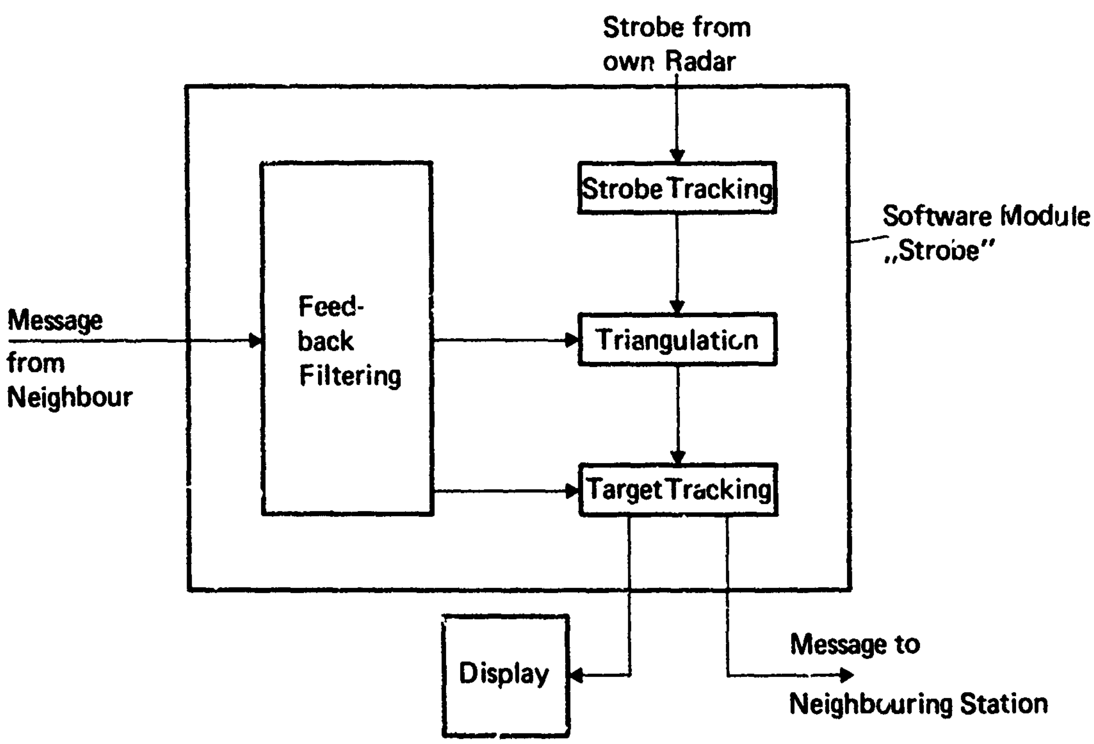


Fig. 18 Strobe Evaluation

DISCUSSION

G.Binias, FRG

Is the track initiation procedure dependent on the clutter environment?

Author's Reply

No, the track initiation procedure is fixed The parameters are variable.

G.Binias, FRG

Which method of plot-to-track association do you use for formation tracking?

Author's Reply

We don't try to track formation flights. We track targets flying in formation separately, as you can see from Figure 17.

A NETTING APPROACH TO AUTOMATIC RADAR TRACK INITIATION, ASSOCIATION, AND TRACKING IN AIR SURVEILLANCE SYSTEMS

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SUMMARY

This paper describes one of several promising concepts for netting radars in a tactical air surveillance system. This concept employs track-while-scan radars having scan periods of from 4 to 12 seconds. Such scan periods are too long to yield an acceptably high probability of automatic association of measurements with tracks when the surveillance region contains many highly maneuverable targets. As presented, the radars overcome this limitation by being connected into a non-hierarchical net over which measurement data is pooled. In the system concept described, most targets will be seen by twenty or more radars. If all radars able to see a target shared the resulting data with the entire system, the communications bandwidth required would be excessive. To avoid this problem, an algorithm was devised that dynamically selects a "best" subset of the system's radars to track each target, thus simultaneously achieving a high probability of correct association (and hence of maintaining track) while requiring reasonable communications bandwidths. This performance is achieved without centralized control. The concept was verified using a detailed computer simulation called TACRAN (Tactical Air Control Radar Net); some simulation results are presented.

1. INTRODUCTION

The internetting of radars in a tactical air surveillance system offers a number of advantages over non-netted or hierarchically netted radars. Besides increasing the system's ability to survive the loss of individual radars and communication links, internetting can be used to improve track initiation, association (or correlation), and track.

This paper presents some results of a study [Deley and Ballentine, 1978] whose objective was "to determine the functional and data processing requirements for improving certain elements such as track initiation, tracking, track correlation and message processing related to future tactical forward area surveillance concepts." The study was performed by General Research Corporation for the Air Force Systems Command's Electronic Systems Division.

Basic System Concept. The basic system concept investigated was conceived at ESD and the MITRE Corporation. In it all sensor elements are netted to provide for more system survivability and effective low-altitude surveillance coverage. To the extent possible, each node in the network (a radar and its data processor) is connected by line-of-sight communications to its three or four nearest neighbors (where possible), as shown in Figure 1, thus providing a non-hierarchical network.

The basic output of the system is a file of System Tracks, which are representations of the flight paths of all the aircraft in the surveillance volume. A System Track File is maintained at each node and (suitably displayed) is used in planning and carrying out air operations. This file need not be very accurate, a fact used to advantage in the system concept considered.

Radar Types Considered. The study considered a variety of radar types, data processing algorithms, and system concepts. Much of the study (and most of this paper) concerned track-while-scan radars with antennas mechanically steered in azimuth and with a relatively long (4-12 seconds) scan period. Elevation information is obtained either from separate feed horns or, for phased arrays, electronic steering. A principal problem with this type of radar is that the data rate is too low to achieve reliable association of measurements with tracks when there are many highly maneuverable targets. Thus, some method of combining data from several radars is required.

Other radar types considered in the study (but not here) included fast-scan (1-2 seconds) track-while-scan radars and fixed phased arrays with single faces as well as arrays with hemispherical coverage. Both fast mechanically scanned reflectors and stationary phased arrays can be operated in a "scan-while-track" mode, whereby track is maintained by specific radar measurements directed by the radar data processor, and surveillance is a slower background function.

Algorithms. The primary algorithms investigated include automatic track initiation, association of measurements with tracks, and track update, with the emphasis on the last two. Other algorithms included track file maintenance and message processing.

Netting Concepts. While there are many possible netting concepts, this study considered only the direct internetting of radars in a nonstructured (lattice) network. This netting type is highly resilient to failures of nodes and links. Possible alternative netting structures include ones with such descriptive names as tree, star, ring, and others. In the simplest network, radars do not interchange data but rather forward it upward in a hierarchical, or tree, network. In more complex systems, data is interchanged between radars to enhance overall system performance. This interchange of data can range from the simple handover of a target from one radar to another to the full interchange of measurements between radars. Networks are also differentiated by their control structure. Control can be centralized, with a single node controlling the network at any given time, or it can be distributed, with control decisions made independently by each node, hopefully in a coordinated fashion. As distributed control has some potential advantages in system survivability, this study concentrated on distributed techniques.

System Concepts. The study emphasized system concepts with reasonable communications bandwidths and high system survivability--that is, systems that degrade slowly in the event of component loss. While the emphasis was on systems having a System Track File at each node, other concepts in which the location of the System Track File is more limited and in which only local Track Files exist at the radars were also investigated. The results of the entire study are given in the Final Report.

This paper considers mechanically scanned track-while-scan radars having scan periods of 4-12 seconds, too long for reliable association of measurements by a single radar. It is concerned with a system concept in which selected radars are used for tracking. The paper describes the system concept and the major algorithms used in the system, and presents some simulated results indicative of the performance of the system.

2. PROBLEM DESCRIPTION

The specific system concept described in this paper consists of a network of mechanically scanned radars as depicted in Figure 2. The netted radars are deployed approximately 30 km apart on an irregular grid to provide low altitude coverage and line-of-sight communications.

The radars have a range considerably longer than 30 km, and thus provide a high degree of overlap. To size the problem, it is assumed that the radar range is 80 km, that up to 25 radars can see most aircraft (i.e., those that are not at very low altitudes), and that each radar sees as many as 350 targets at a time.

Because of the considerable maneuver capability attributed to the targets to be tracked (as much as 8-10 g's), it was determined that the track data rate should be at least 0.5 Hz to reliably maintain track, corresponding to a measurement interval of 2 seconds or less. The association errors due to maximum aircraft acceleration over such a time interval are comparable in magnitude to the measurement errors of radars likely to be used in this application. As the 4-12-second scan periods of the radars considered are too long to permit a high probability of association of measurements with tracks, the measurements from several radars must be combined to achieve a higher effective data rate.

Conceptually, the simplest way of combining data is for all radars to send all measurements to all other radars. While this imposes a large computational load, it should be feasible with the data processing technology of the future. The principal problem with this straightforward approach is that the load imposed on the communication links by many tracks is undesirably large--on the order of a megabit per second for the maximum aircraft densities considered.

Thus a concise statement of the problem considered in this paper is as follows: For a network of slow-scan track-while-scan radars, define and analyze a system concept that

1. Provides a System Track File at every node
2. Has a high probability of correct association
3. Requires a low communication bandwidth
4. Has a high probability of system survivability

3. A SYSTEM CONCEPT

The system concept described in the rest of this paper was designed to satisfy the four objectives given above. The purpose of defining this concept in detail is to demonstrate that it is possible to satisfy the somewhat conflicting objectives. It should be considered as a "proof of concept," not a fully defined, optimized system.

The elements of the concept are as follows: The principal output of the system is a System Track File (STF) whose required accuracy, a system parameter, is assumed to be low, perhaps on the order of a kilometer or so. All nodes have a copy of the STF. To reduce the communication bandwidth, the STF is updated as infrequently as possible consistent with the required accuracy.

Each aircraft is tracked cooperatively by a few selected radars. The resulting measurements are pooled to yield a single track on each aircraft at an effective data rate that is higher than the scan rate of the individual radars. Each tracking radar has a copy of this track, which is called the "Distributed Local Track."

The number of radars tracking each aircraft is kept to a minimum to minimize communication bandwidth. The set of tracking radars is carefully selected to ensure that the pooled measurements are reasonably evenly spaced in time, since it does not help association if all of the radars make a measurement at the same time causing an entire scan period to elapse between measurements. Other factors described later are also considered in selecting the set of tracking radars for each aircraft.

The set of tracking radars for each target dynamically changes with time based on criteria which are evaluated whenever a measurement is made. The determination and control of which radars track which targets is totally distributed with no centralized controller.

Thus, for each target there are three types of nodes (radar/data processors): (1) those that are actively tracking the target, pooling their measurements to accomplish this task, (2) those that can see the target but are not presently tracking it, and (3) those that cannot presently see the target. Nodes can change type at any time.

4. ALGORITHMS

Before describing the system concept in more detail (in Sec. 5 below), some of the basic algorithms used will be discussed.

Track Initiation. This function is performed by individual radars after determining that a new measurement does not associate with a track in the System Track File. Measurements from three consecutive scans are required to initiate track. Association of the second measurement with the first is based simply on their separation relative to the distance an aircraft could fly at its assumed maximum speed; the third measurement must then credibly associate with the tentative track established by the first two measurements. The maximum speed used in the algorithm can depend on altitude and whether it is vertical or

horizontal. The thresholds are set to give a very high probability of initiating a track on a true aircraft trajectory. The false trajectories generated eventually die due to lack of association with future measurements.

Association. In the dense target environment, associating measurements with tracks is a particularly serious problem, especially for a fully automated system. Given that 8g-10g maneuvers are possible in a tactical environment, it is imperative that the track rate be reasonably high (on the order of a measurement every one or two seconds). Otherwise the targets may deviate a considerable distance from the predicted track, increasing the possibility that they may be mixed up in the association process.

Since the track-while-scan radars considered do not achieve this rate, measurements from several radars must be combined, but not from a randomly selected set of radars--two measurements that are close in time (separated by less than about a second) do not materially help the associated problem since the measurement errors exceed the displacement due to maneuvers over short time intervals. Rather, the set of radars selected should produce measurements that are reasonably evenly spaced in time.

Association is performed by considering all sets of measurements in a given region simultaneously, rather than by considering measurement-track pairs individually. The algorithm creates a matrix of measurements versus tracks, with the squared distance between them as the elements of the matrix. The unique pairings of measurements with tracks is then accomplished in a manner that minimizes the sum of the squared distances. This is the well-known assignment problem in network theory and efficient algorithms are available to find the minimum.

Another technique for improving the probability of correct association involves more precisely defining the region a maneuvering aircraft can reach since the last track update. The maximum maneuver capability for each aircraft type depends on (1) whether the aircraft's acceleration is tangential or normal, vertical or horizontal, (2) its velocity, and (3) its altitude. The exact shape of the association region, which includes track (model) and measurement errors as well as maneuvers, is complex and difficult to model in a computer. Approximations to the region, which is not even convex, are required.

Tracking. Several types of track filters (Kalman, α-β, etc.) were investigated for use in the system concept. In general, with highly maneuverable targets, it can be shown that Kalman filtering does not improve the quality of the track. Thus, it was decided to use a simple, weighted least-squares fit of the last few measurement points to a quadratic polynomial. The number of points chosen should be enough to provide some smoothing, but not so many that old and irrelevant data is used.

The System Track differs from the Distributed Local Track (DLT) in that it isn't updated every measurement time. It is identical to the DLT when updated, but it is updated only when it deviates from the DLT by a system-specified distance. The second-degree polynomial is used for tracking to help reduce the frequency with which the System Track is updated.

5. DETAILED SYSTEM DESCRIPTION

Track File Structure. As shown in Fig. 3, at each node (radar/data processor) the System Track File (STF) is partitioned into two parts: (1) those tracks being actively tracked by this node [this partition is called the "Distributed Local Track File" (DLTF)], and (2) those tracks not being tracked by this node. The latter file is called the "Non-Track File" (NTF). All of the tracks in the entire system are in the System Track File; however, membership in the two partitions will be different at different nodes. Regardless of which partition a particular track is in, the system track data will be identical throughout the system to the extent permitted by communication delays.

The first partition, the Distributed Local Track File, has, in addition to the system track data, other data called the Distributed Local Track data. The latter data contains the up-to-date track on a target and is identical at each of the tracking nodes.

Logic Flow. The (simplified) system flow diagram is shown in Fig. 4 as it is simulated on a digital computer. The figure depicts a number of radars connected to data processors. Each radar makes measurements on aircraft whose positions are determined by the Aircraft Flight Simulation. Each data processor is connected to the network, represented by the Communications Network Simulation. The data processing logic implemented at each node of the system is shown in the box labeled "Data Processor #1."

Association Logic. At each radar/data processor node a new return (measurement) obtained from the radar is first associated with the Distributed Local Track File. If it doesn't successfully associate, it is next associated with the Non-Track File. This two-part association, designed to save both data processing and communication resources, assumes that association with the DLTF, which is more accurate than the NTF, will be correct with a high probability. Association with the NTF is more difficult since the NTF track is sometimes not sufficiently accurate to provide a high association probability. If more than one track associates with the measurement (a situation which should occur relatively infrequently), then this node does not have sufficient information to resolve the conflict. In this case the node sends a message to one of the trackers of each track within the association volume asking for a more accurate computation of the distance between the measurement and the track. (An integral part of the system concept is that each System Track includes an up-to-date list of the radars that are participating in the track, thus this information is known to all nodes in the system.) Using this more accurate distance, an unambiguous association decision is then made using the association algorithm described in the previous section.

Track Initiation Logic. If the measurement doesn't associate with either the DLTF or the NTF, then Track Initiation is performed. First the measurement is checked against the tentative two-measurement tracks in the Track Initiation File. If it associates, a new track is initiated in the DLTF. If it doesn't, the measurement is used in an attempt to start a track with a measurement saved from the last scan. If an association is made (based on maximum speed) a new tentative track is put into the (two-scan) Track Initiation File. In either case, the measurement is saved for association with measurements on the next scan.

Tracker Selection Logic. If the measurement associates with the DLTF (Fig. 4, top) this radar is a tracker of the target. In this case a part of the logic is entered that deals with dynamically selecting the best set of trackers without using centralized control. This part performs the computations and makes the decisions needed to answer the question "Should I continue to be a tracker?" In answering this logic considers (1) the present number of trackers, (2) the next expected reception times of the other trackers, (3) the time spacing of the returns, (4) the relative ranges and range rates of the target as seen by all trackers, and (5) expectation that the target will soon be out of range or in the blind cone over the tracking radar. All of these factors are evaluated without any communications with other nodes. If the answer to the question is "No, I shouldn't continue to be a tracker," a message is sent to all other nodes advising that this radar is no longer a tracker of this target. If the answer is "Yes, I should continue to be a tracker," then the measurement is used to update the Distributed Local Track and the measurement is sent to the other trackers to update their DLTs. The node can also send a special "Help" message if it would like for some reason to be replaced by another node.

If the measurement associates with the Non-Track File, the node asks the question "Should I become a tracker?" This logic is similar to the logic used by a present tracker to determine if it should continue to be a tracker. The node may decide to add itself as a tracker, or to replace a present tracker. In either case, it sends a message to every node advising of this decision.

If the node decides to become a tracker, it sends a message to one of the present trackers asking for a copy of the Distributed Local Track on the target. On receiving the DLT it uses the same logic as if it were already a tracker.

Track Update Logic. The Distributed Local Track is updated by the weighted least-squares algorithms previously described. Next, it is determined if the System Track should be updated based on two criteria: (1) the System Track has deviated from the Distributed Local Track by a given distance, or (2) a maximum time (a minute or so) has elapsed. If either of these criteria are met, the System Track is made identical to the Distributed Local Track and the update is sent to the entire system.

Communications. The system concept just described requires two different classes of messages: (1) System Messages, which are messages delivered to all nodes in a system, and (2) Directed Messages, which are delivered to one or more specific nodes. As described, the concept requires four distinct System Messages and five distinct Directed Messages. The average bandwidth of each link required to transmit all of these messages is given in Table 1 as a function of a number of parameters. As an example, the average bandwidth of each link in a 70-node system with 110 two-way links tracking 1,000 aircraft is about 35 kbits/second, which is reasonable considering the large number of aircraft being tracked. The largest contributors to bandwidth are the System Track File (STF) updates. The other message types are required to increase the efficiency of the overall systems. The bandwidth added by these other messages is far less than the bandwidth saved by reducing the number of STF updates to the minimum possible.

6. SIMULATION RESULTS

The logic described in the last section was programmed into a digital computer simulation called TACRAN (Tactical Air Control Radar Net). The simulation geometry for one set of runs is shown in Fig. 5. These runs included four radar/data processor nodes, three aircraft, and the four two-way communication links shown. Two of the radars (1 and 3) are near their maximum range from the targets, Radar 4 is at a

TABLE 1

COMMUNICATION BANDWIDTH REQUIREMENTS

Message	Message Length, Bits			Links per Message	Bits/Link per Message	Message/s per Target	kbits/s per Link	
	Header	Text	Total				Equation	Example
Distance Request	10*	85	95	2	190/L	$F(N_S-N_T)/T_S$	$0.190N_A F(N_S-N_T)/LT_S$	3.2
Distance	10*	32	42	2	84/L	$F(N_S-N_T)/T_S$	$0.084N_A F(N_S-N_T)/LT_S$	1.4
DLT Request	52	24	76	2	152/L	$1/T_C$	$0.152N_A/LT_C$	0
DLT	52	439	491	2	982/L	$1/T_C$	$0.982N_A/LT_C$	0.2
Measurement	60	77	137	3	411/L	N_T/T_S	$0.411N_A N_T/LT_S$	1.9
STF Update	96**	206	302	N-1	302(N-1)/L	$1/T_U$	$0.302N_A(N-1)/LT_U$	23.7
Drop Tracker	96**	24	120	N-1	120(N-1)/L	$1/T_C$	$0.12N_A(N-1)/LT_C$	1.5
Add Tracker	96**	47	143	N-1	143(N-1)/L	$1/T_C$	$0.143N_A(N-1)/LT_C$	1.8
Help	96**	40	136	N-1	136(N-1)/L	$1/T_H$	$0.136N_A(N-1)/LT_H$	0.9
							TOTAL	34.6 kbits/s

Symbol	Description	Example Values	Symbol	Description	Example Values
N	Number of nodes (radars)	70	T_S	Average scan time	6 s
N_S	Number of radars that can see a target	25	T_U	Average time between STF updates	8 s
N_T	Number of radars tracking a threat	3	T_C	Average time between change of tracking radars	50 s
L	Number of links	110	T_H	Average time between help messages	100 s
N_A	Number of aircraft (targets)	1,000	F	Fraction of measurements for which a distance must be obtained	0.5

*Assumes that an average of 5 requests are combined in each message.

**Average number of receiver addresses per message = 6.5.

medium range. and Radar 2, is at close range. The ranges, of course, effect the signal-to-noise ratios and hence the tracking accuracies.

As an example of the performance of the system, one computer run is briefly described. Three tracking radars each having a scan period of 6 seconds are required to achieve a desired effective measurement interval of 2 seconds. Track was initiated on Aircraft 1 by Radar 4 at 19.2 seconds. During the next 4 seconds Radars 1 and 2 added themselves as trackers. At 35.9 seconds, Aircraft 1 was approaching the maximum range of Radar 1, and Radar 3 added itself as a tracker and dropped Radar 1. Aircraft 3 was acquired by Radar 2 at 22.4 seconds. Shortly thereafter, Radars 3 and 4 added themselves as trackers, and this set of three radars continued tracking during the rest of the run.

The circular path of Aircraft 2 caused a more interesting history. Acquisition was by Radar 4 at 19.8 seconds, with Redar 2 adding itself as a tracker at 22.0 seconds and Radar 3 at 23.9 seconds. At 63.4 seconds Radar 1 notices that the aircraft is flying out of Radar 3's range so it replaces Radar 3 as a tracker. At 77.9 seconds the reverse occurs, and Radar 3 replaces Radar 1.

The Distributed Local Track performance obtained is shown in Figure 6 for part of the trajectory of Aircraft 3. The measurement standard deviations given in the figure show that the measurements from Radar 3 are much noisier than the others, as expected from its greater range. Five measurements spanning the last 8 seconds were used in the filter.

The corresponding System Track is shown in Figure 7. This track is updated whenever it deviates from the Distributed Local Track by more than a kilometer.

7. SUMMARY

Netting can be used to increase the effective data rate of slow-scan track-while scan radars. The resulting increase in data rate increases the probability of correct association of measurements with tracks and thus improves the track performance of the system. This paper has presented a concept for achieving the desired effective higher data rate while at the same time maintaining a reasonable communications bandwidth.

REFERENCES

Deley, G.W. and Ballantine, J.H., 1978, Tactical Forward Area Surveillance and Control Internetting Study, Final Report, General Research Corporation CR-1-814.

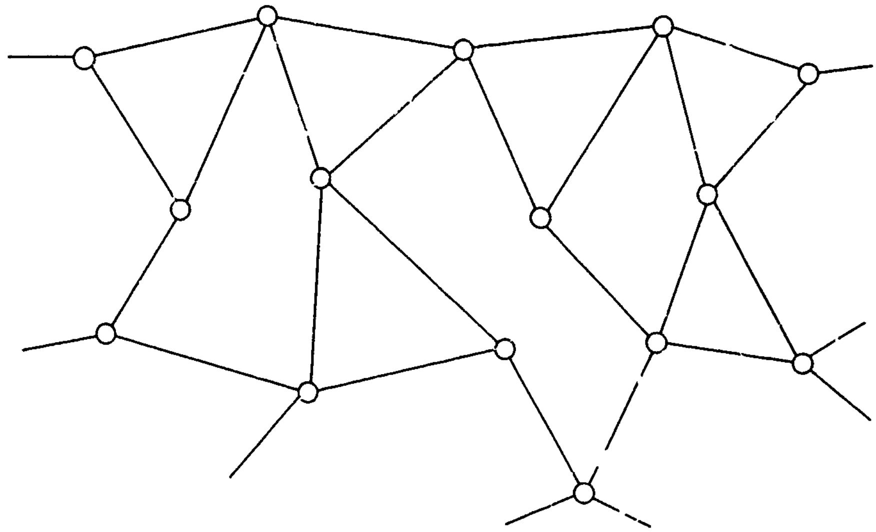


Fig.1 Non-hierarchical radar network

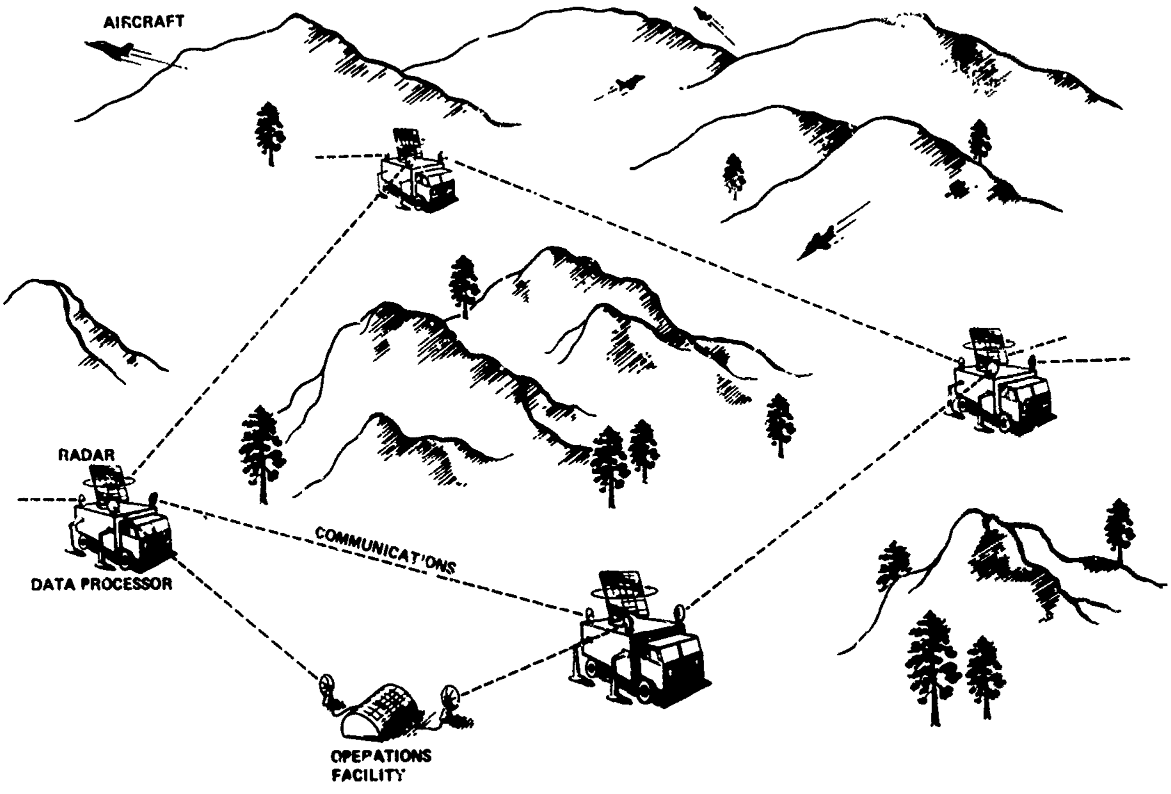


Fig.2 Portion of tactical air control radar net

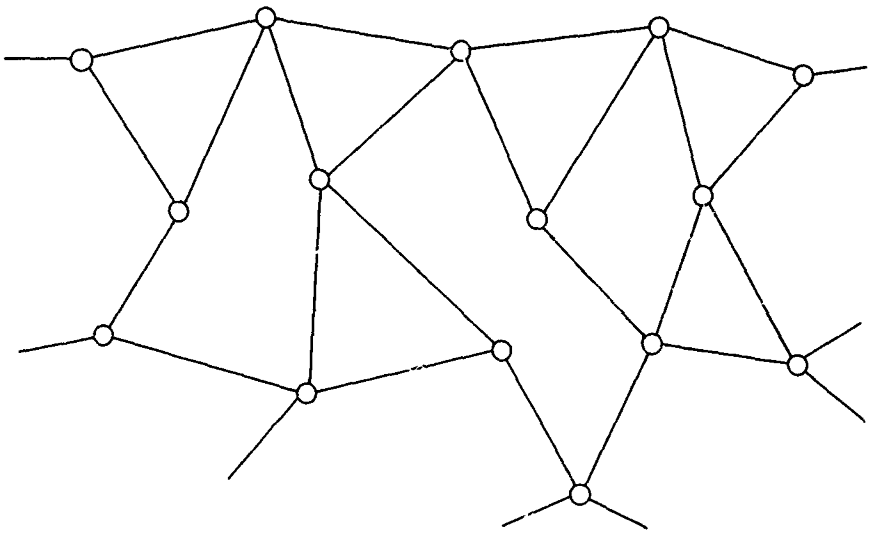


Fig.1 Non-hierarchical radar network

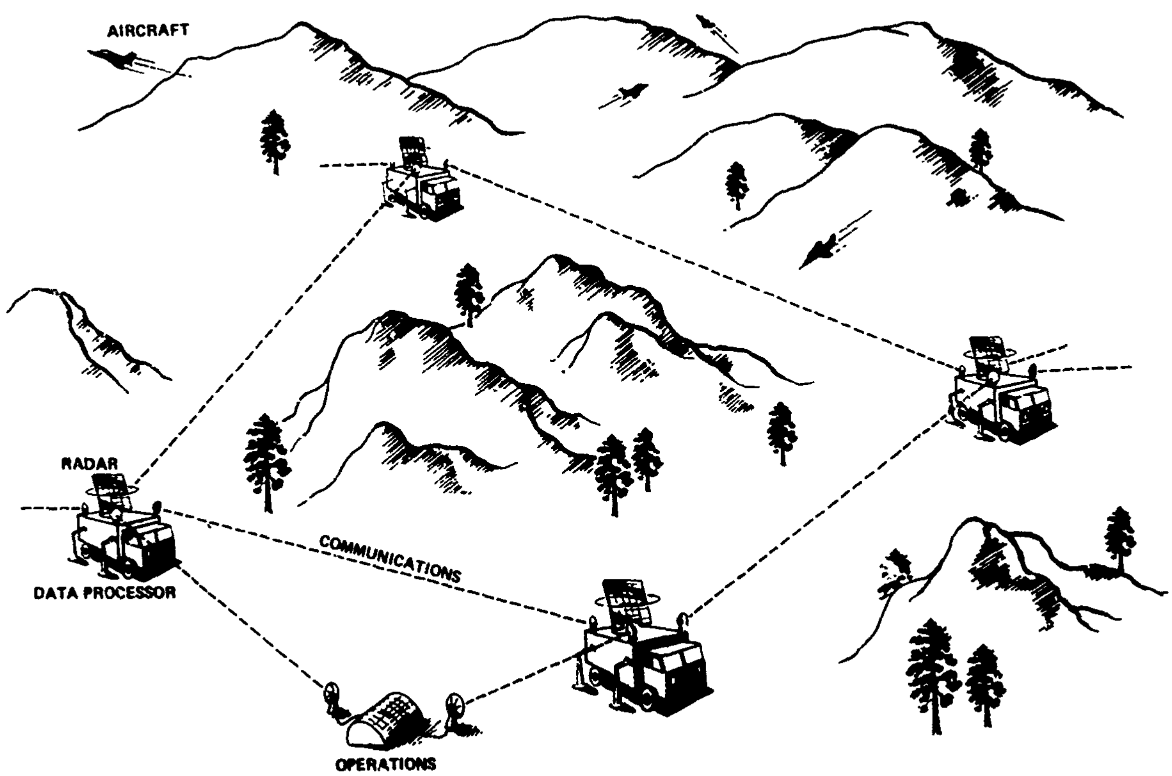


Fig.2 Portion of tactical air control radar net

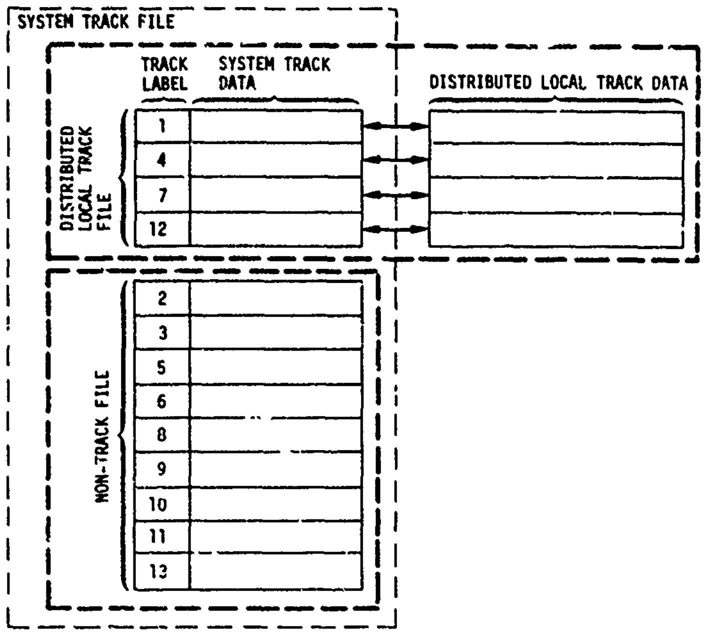


Fig.3 Track file structure

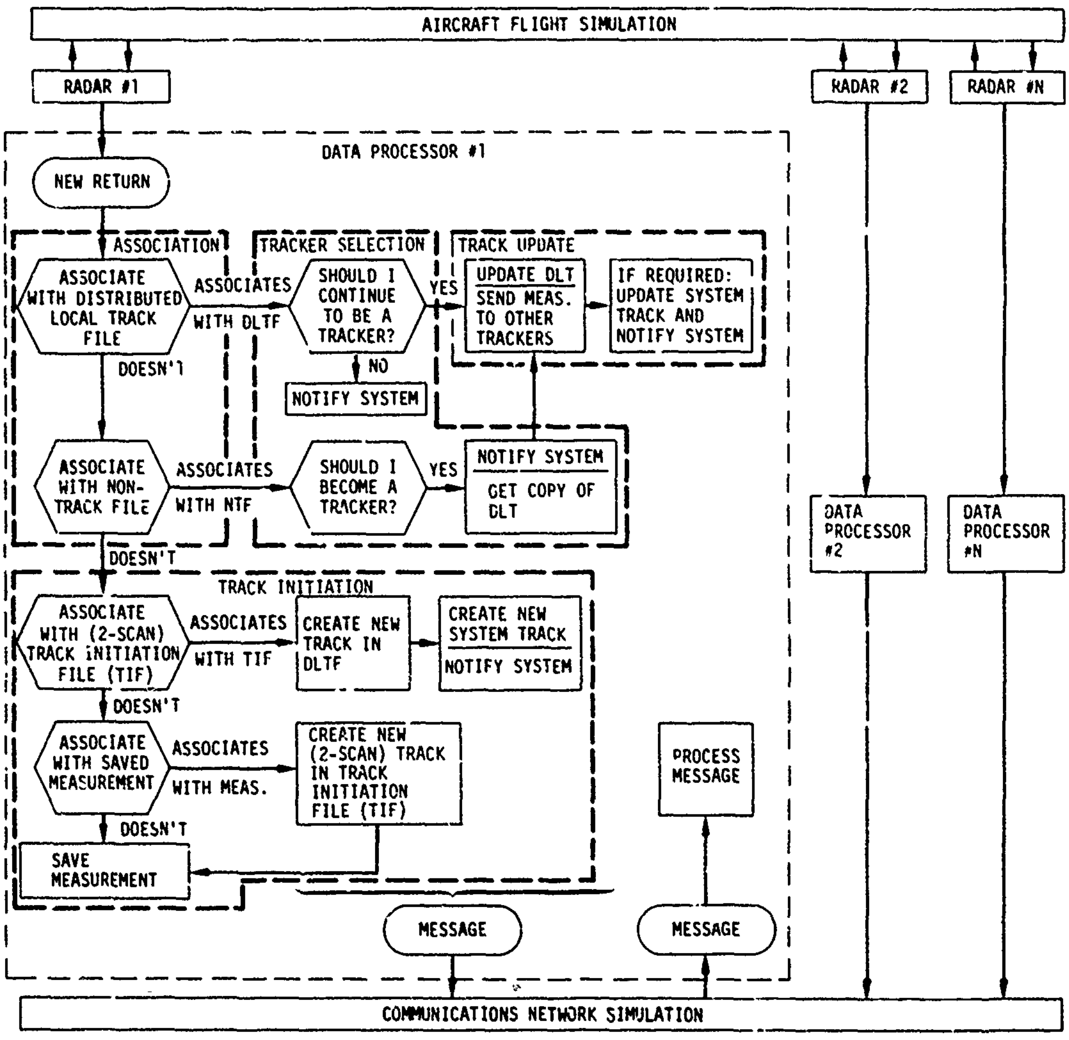


Fig.4 Tactical air control radar net simulation (TACRAN version 3)

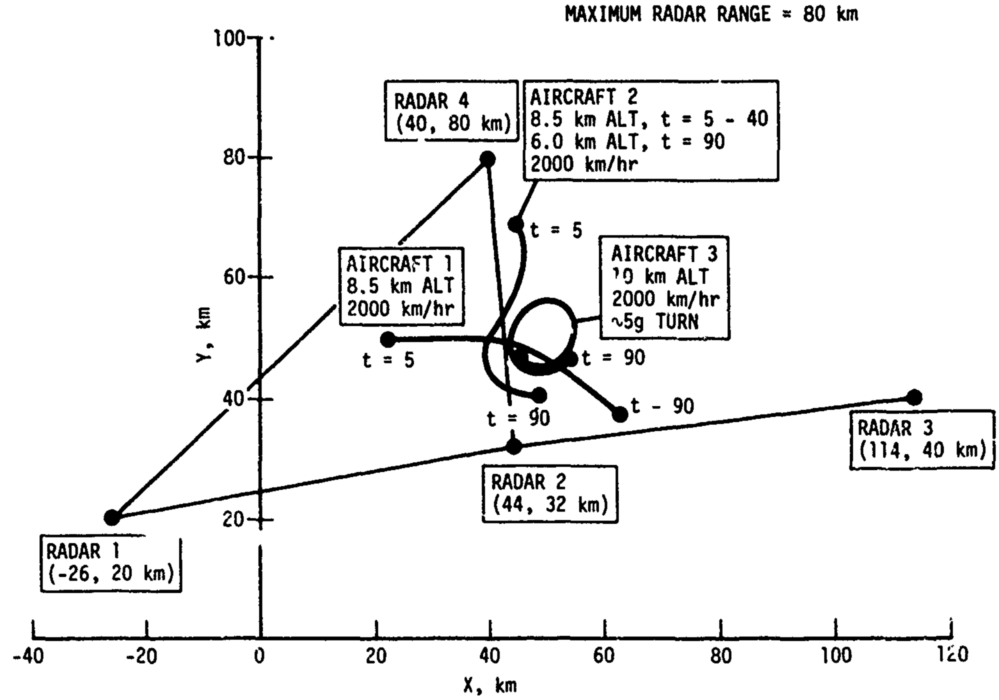


Fig.5 Example simulation geometry

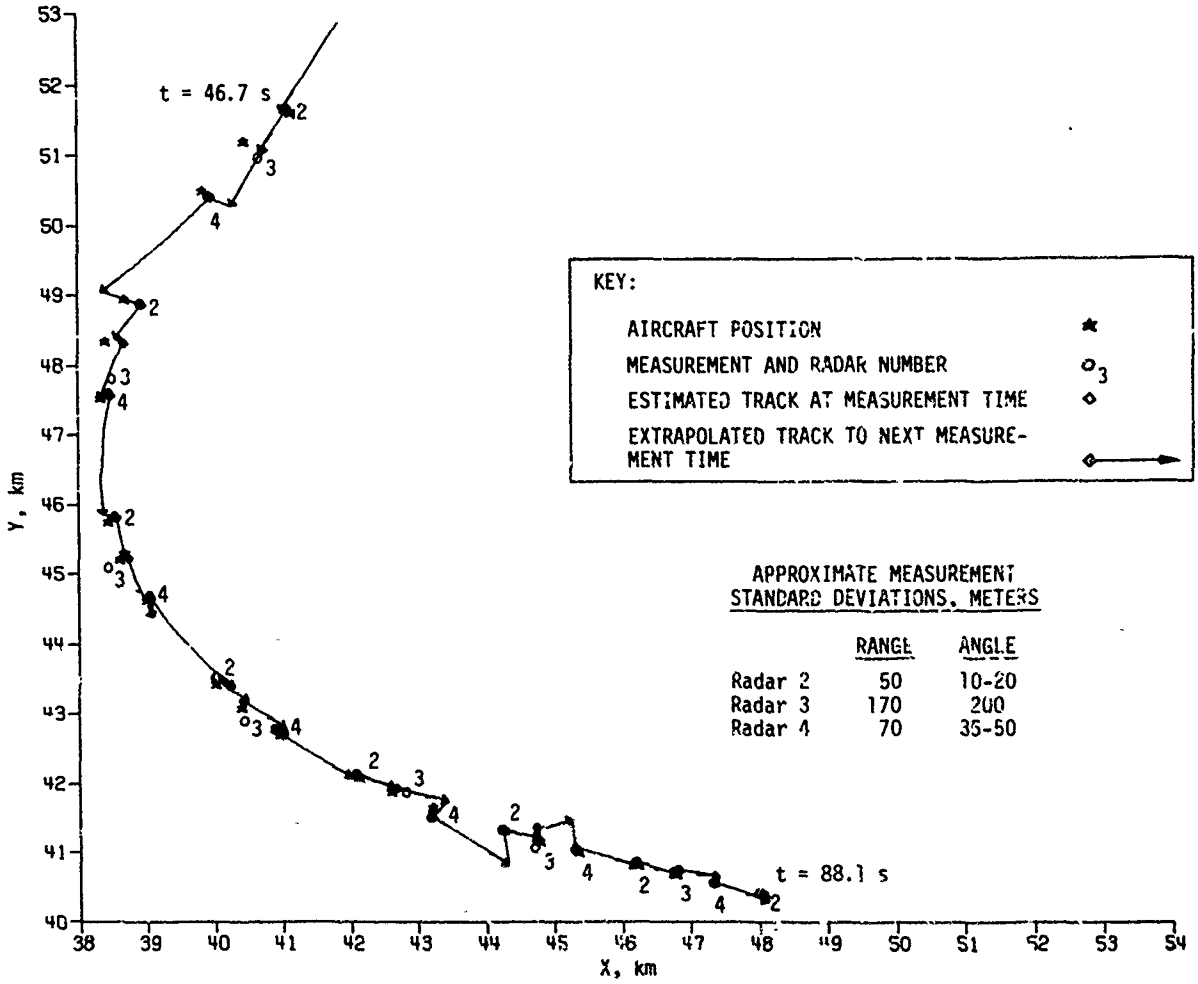


Fig.7 System track performance for aircraft no. 3

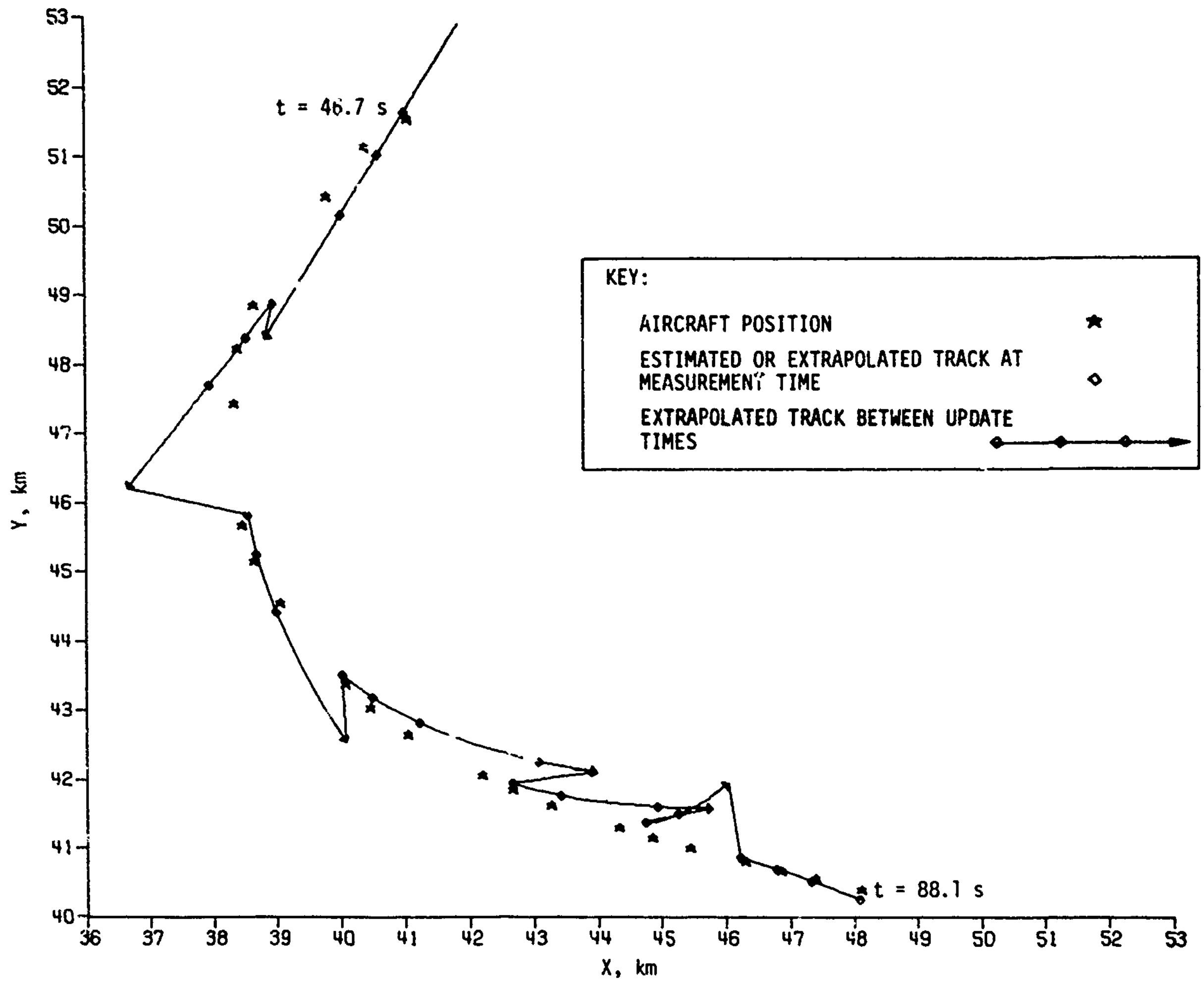


Fig.6 Distributed local track performance for aircraft no. 3

DISCUSSION

H.Kaltschmidt, FRG

Have you considered the use of a satellite communication system instead of line of sight netting?

Author's Reply

Yes, but we are concerned with ease of jamming this link.

H.Kaltschmidt, FRG

What bit error probability is allowed?

Author's Reply

This was not investigated.

H.Kaltschmidt, FRG

Would the delay time in a satellite link be a serious problem?

Author's Reply

The delay time is a small fraction of the track update period, so it is probably not a serious problem, but this was not investigated in any detail.

H.B.Driessen, Netherlands

Is the system track update time of 8 seconds (Figure 7) compatible with the required update time of 1–3 seconds (Section 2)?

Author's Reply

Tracking is performed with the distributed local track, and it is here that the 1–3 second requirement exists. The system track is updated from the distributed local track (rather than from the measurements) and the accuracy requirements of the system track are independent of those for the distributed local track.

POURSUITE AUTOMATIQUE RADAR PRIMAIRE
DANS UN CENTRE D'APPROCHE ET DE RECUEIL
MILITAIRE

A.Poch
Chef de Projet
SINTRA
France

La poursuite automatique radar primaire dans un centre d'approche et de recueil militaire est confrontée à des problèmes très spécifiques liés à l'environnement et à l'exploitation opérationnelle. Ceci conduit à développer des algorithmes particuliers et à un temps de mise en oeuvre extrêmement court adaptés au traitement des cibles évoluant en zones denses et à basse altitude.

Ces algorithmes traitent en particulier les fonctions principales suivantes :

- constitution d'une "carte mouvante" entretenue en temps réel des plots reconnus de la couverture, ceci permettant une accélération de l'initialisation, un accroissement de la probabilité du suivi, et une élimination des fausses pistes,
- initialisation automatique rapide sur plots à partir de critères auto-adaptatifs en fonction de la zone de création dans la couverture radar : zone de recueil, zone d'atterrissage/décollage, zones de surveillance,
- association plots-pistes tenant compte des conditions propres à l'approche : échos fixes, clutters atmosphériques, vitesses, performances et situations des cibles très disparates,
- adaptation automatique en temps réel des paramètres de lissage en fonction des évolutions des cibles (accélérations, décélérations, virages, manque de détection radar).

L'ensemble de ces traitements constitue un programme compact qui a été implanté dans un minicalculateur et a permis de réaliser l'automatisation de l'exploitation radar d'un centre d'approche et de recueil en FRANCE avec le soutien des Services Techniques des Télécommunications de l'Air.

1 - PRESENTATION DU CYCLE DE POURSUITE

Le module de poursuite a pour but essentiel la constitution des tables des pistes à partir des plots reçus de l'extracteur.

Après une période d'initialisation (automatique ou manuelle), les pistes sont établies.

Le programme doit alors essentiellement au cours d'un nouveau tour d'antenne :

- dans la mesure du possible, associer à chaque piste le plot qui a été fourni par l'avion représenté par cette piste,
- à l'aide de ce nouveau plot, donner une nouvelle estimation de la position et de la vitesse de l'avion, ceci constitue l'avancement de la piste,
- avec les plots qui n'ont pas été associés à une piste, dans certaines conditions, créer de nouvelles pistes, ceci constitue l'initialisation automatique des pistes.

L'espace aérien est divisé en 16 secteurs de 22°5.

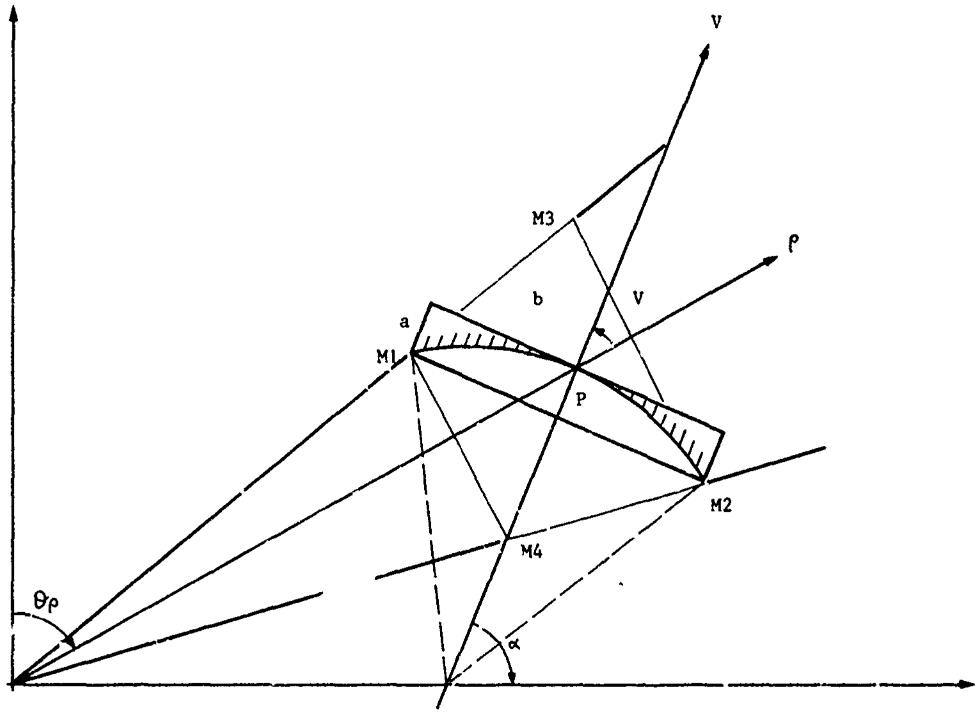
Le module de poursuite est décrit dans les chapitres suivants.

2 - RANGEMENT DES PISTES

Rangement en données locales des pistes (en création extrapolée ou ferme) qui risquent d'être concernées par les plots du secteur "n", ce, compte tenu de leur position prédite.

Détermination pour chaque piste rangée en donnée locale d'une fenêtre de prédiction (zone définie autour du point prédit dans laquelle doit se trouver le plot quelle que soit l'évolution de l'avion).

FENETRE D'EVOLUTION $\rho\ \theta$



Les dimensions de la fenêtre d'évolution $\rho\ \theta$ sont :

$$\Delta\rho+ = \max\left[a, (b \sin V - a \cos V)\right]$$
$$\Delta\rho- = b \sin V + a \cos V$$
$$\Delta\theta+ = b \cos V + a \sin V$$
$$\Delta\theta- = \max\left[a, (b \cos V - a \sin V)\right]$$

Ces dimensions, après un ou plusieurs manques, deviennent :

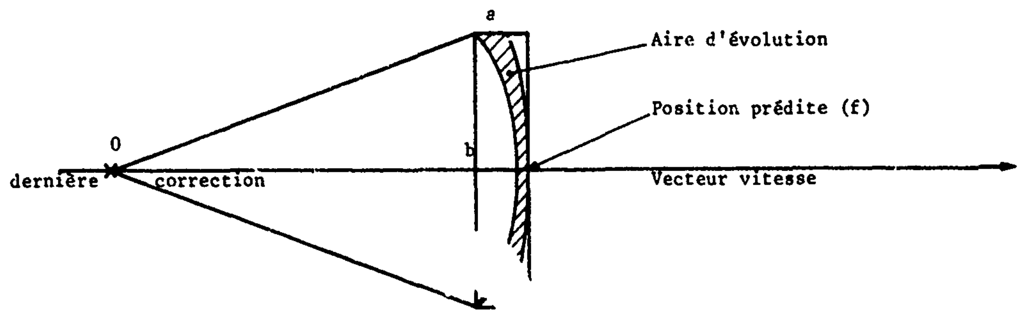
$$\Delta\rho+ = \Delta\rho+ + VT\ (1 - \cos V)\ NM-1$$
$$\Delta\rho- = \Delta\rho- + VT\ (1 + \cos V)\ NM-1$$
$$\Delta\theta+ = \Delta\theta+ + VT\ (1 - \sin V)\ NM-1$$
$$\Delta\theta- = \Delta\theta- + VT\ (1 + \sin V)\ NM-1$$

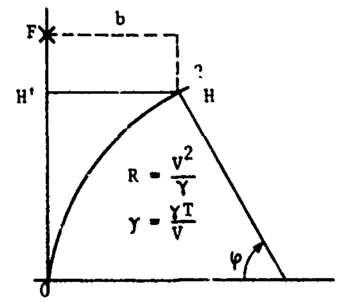
3 - RANGEMENT DES PLOTS

Deux tâches distinctes :

- stockage des plots (3 tours d'antenne).
- visualisation des plots.

FENETRE D'EVOLUTION



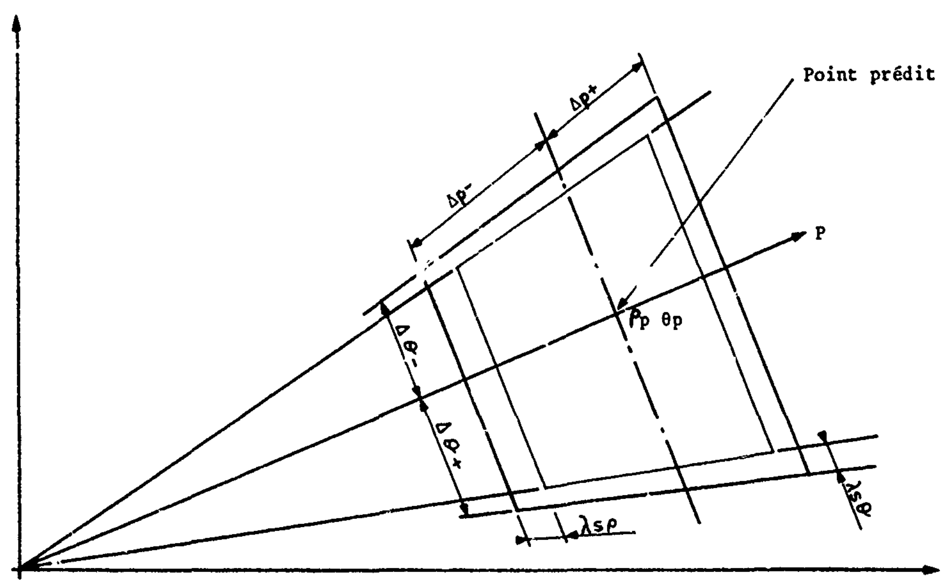


V = Vitesse

T = Période de rotation

γ = Accélaration transverse maxi

FENETRE DE PREDICTION EN $\rho\ \theta$



Les bornes de la fenêtre de prédiction sont :

$$\rho_{min} = \rho_{prédit} - \Delta\rho- \; - \; 2{,}5 \; \sqrt{1+F} \; \tau\rho$$
$$\rho_{max} \quad \rho_p \quad + \Delta\rho+ \; + \; 2{,}5 \; \sqrt{1+F} \; \tau\rho$$
$$\theta_{min} \quad \theta_p \quad - \Delta\theta- \; - \; 2{,}5 \; \sqrt{1+F} \; \tau\theta$$
$$\theta_{max} \quad \theta_p \quad + \Delta\theta+ \; + \; 2{,}5 \; \sqrt{1+F} \; \tau\theta$$

4 - ASSOCIATION PLOT-PISTE

Réaliser l'association plot-piste optimum.

Pour cela, il faut pondérer en probabilité la validité de l'affectation d'un plot à une piste.

Calcul de l'écart réduit (écart normé par l'écart type de la précision de prédiction) pour chaque couple plot-piste.

$$\mu = \frac{1}{1+F}\left[\frac{\Delta\rho^2}{\tau\rho^2} + \frac{\Delta\theta^2}{\tau\rho^2}\right]$$

$\Delta\rho\ (\Delta\theta) = \rho_{plot} - \rho_{prédit}$

$\tau\rho^2$, $\tau\theta^2$ sont les variances de la mesure du plot.

F : Facteur multiplicatif de ces variances pour la prévision dépendant du lissage.

4.1 - Attribution des plots aux pistes

Pour chaque piste fermée ou prolongée du secteur n - 1, recherche des plots des secteurs voisins (4 secteurs) qui sont à l'intérieur de la fenêtre de prédiction.

Pour chaque plot à l'intérieur de la fenêtre, mémorisation de :

- adresse du plot dans la table de la piste,
- adresse de la piste dans la table du plot,
- l'écart réduit μ du plot au point prévu.

Pour chaque piste en création du secteur n-1, recherche des plots qui sont a l'intérieur de la fenêtre de bruit.

A la fin de l'attribution, les pistes du secteur n-1 se voient attribuer 0, 1 ou "p" plots.

4.2 - CORRELATION DES PLOTS AUX PISTES

La corrélation se fait pour les pistes du secteur n-2.

Deux cycles de corrélation :

CORRELATION 1 :

Association plot-piste qui ne présente aucune ambiguïté.

Trois étapes :

- Etape 1 : Pistes ayant 1 plot monopiste situé dans la fenêtre de bruit,
- Etape 2 : Pistes ayant "p" plots monopistes situés dans la fenêtre de bruit,
- Etape 3 : Pistes ayant 1 plot monopiste situé dans la fenêtre d'évolution.

CORRELATION 2 :

Association plot-piste qui présente une ambiguïté.

Sept étapes :

- Etape 1 : Pistes fermes ayant "p" plots monopistes situés dans la fenêtre d'évolution,
- Etape 2 : Pistes fermes n'ayant pas de plot attribué,
- Etape 3 : Pistes prolongées 1 fois ayant "p" plots monopistes situés dans la fenêtre d'évolution aux tours d'antenne n-1 et n,
- Etape 4 : Pistes prolongées 1 fois ayant eu "p" plots monopistes dans la fenêtre spécifique au tour d'antenne n-1 et aucun plot au tour n,
- Etape 5 : Pistes prolongées 2 fois n'ayant pas eu de plot attribué aux tours n-2, n-1 et n,
- Etape 6 : Pistes prolongées 3 fois n'ayant pas eu de plot attribué au tour n,
- Etape 7 : Pistes ayant "p" plots multipistes situés dans la fenêtre de prédiction.

5 - AVANCEMENT DES PISTES

De type α, β

$$\vec{P}_{e,n} = \alpha\vec{P}_{m,n} + (1-\alpha)\,(\vec{P}_{e,n-1} + T\vec{V}_{e,n-1})$$

$$\vec{V}_{e,n} = \frac{\beta}{T}\,(\vec{P}_{m,n} - \vec{P}_{e,n-1}) + (1-\beta)\,\vec{V}_{e,n-1}$$

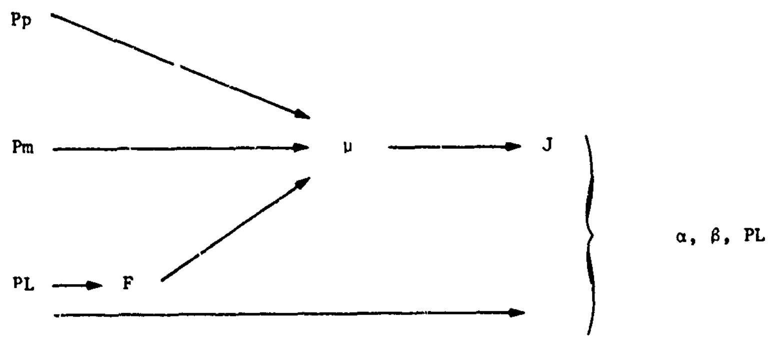
où :

$\vec{P}_{e,n-1}$, $\vec{V}_{e,n-1}$, $\vec{P}_{e,n}$, $\vec{V}_{e,n}$: Positions et vitesses estimées aux pas n-1 et n,

$\vec{P}_{m,n}$: Position mesurée au pas n (c'est-à-dire le plot),

$\vec{T}$: Période d'obtention des divers échantillons (P_n).

LOGIQUE D'AVANCEMENT



6 - INITIALISATION AUTOMATIQUE

PISTES PRIMAIRES

Les pistes en création sont obtenues à partir de 3 plots compatibles répartis sur 3 ou 4 tours d'antenne successifs :

- piste linéaire,
- piste en virage.

ANALYSIS OF SECOND AND THIRD ORDER STEADY-STATE TRACKING FILTERS

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SUMMARY

In a multi-target environment, the heavy processing load on even the most powerful radar tracking systems makes it necessary to sacrifice theoretical optimality for practical feasibility in the tracking process. One approach is to adopt sub-optimal methods for track estimation using steady-state adaptive α-β and α-β-γ filters, which are derived from the Kalman filter and which combine good track-following ability, ease of adaptation to changes in the tracking conditions, and low computational cost.

A theoretically-derived functional relationship between the set of gain coefficients and a system parameter which quantifies the current tracking conditions (viz., target maneuver uncertainty, radar measurement error and track update interval) permits a rapid and near-optimal response to any changes in those conditions. An economical means is developed to incorporate this adaptive feature in a tracking system.

In the α-β(-γ) type of filter, the tracking coordinates are assumed to be decoupled, and are treated separately. In a track-while-scan system, fixed Cartesian coordinates are most often used, for which this assumption is not strictly valid. Coordinate-transformation techniques are described which may be used to compensate for this simplifying approximation. Other aspects of practical implementation of this type of tracking filter are also examined.

The use of steady-state adaptive filters in multi-target air-surveillance tracking systems permits a larger proportion of the available computing time per sensor scan to be allotted to automatic initiation and association tasks. Preliminary simulation results indicate that these filters perform as well as the fully-coupled recursive Kalman filter in cases where the primary requirement is to support the track-association task, that is, to provide dependable automatic coverage rather than very precise estimation of individual tracks. Steady-state, adaptive filters provide the system designer with a practical option in the cost/performance trade-off.

1. INTRODUCTION

In an automatic track-while-scan (TWS) air-surveillance system, the radar sensor reports measurements of target positions (plots) at regular intervals of time to a computer, which then assembles the plots from successive scans into tracks. The computer program must correctly associate new plots with existing tracks and initiate new tracks from reports received on air targets within range of the radar. The association task is aided by tracking filters which combine noisy measurements with track predictions to obtain smoothed updated track estimates. The predicted position of the target for the next radar scan, based on the smoothed estimate of the current position of the target, is used together with the estimated standard deviation of the prediction to determine the location and size of the region of acceptability of new observations on that target. The tracking filter thus plays an essential role in the function of plot-to-track association, in addition to its role of providing accurate estimates of the position and motion of the target.

The literature on the techniques of track filtering (smoothing and prediction) is very large and diverse. One aim of this paper is to attempt to construct a simple framework in which the majority of techniques could be placed and thereby more easily analyzed and compared.

An operational air-surveillance system must be capable of tracking many targets simultaneously, in an environment that may provide large numbers of false target indications due to fixed and moving clutter as well as system noise. The premise of this paper is that the primary task of the tracking computer in such a system is that of track initiation and association, and that these functions should be allotted most of the computational time available. In a system involving a network of sensors, the related task of track registration should also be included in this preferred allotment. The measurement accuracy obtained and the tracking precision required by such systems do not demand the most computationally complex filtering operations. It is essential that the filtering operations give sufficient support to the association procedures; any complexity beyond that necessary for this task is of diminishing value. It is important however that the filter be sufficiently flexible to adjust quickly to changes in the tracking environment. A second aim of this paper, then, is to derive simple, easily implemented, and computationally inexpensive filters which nevertheless retain as far as possible the features of optimality and flexibility which the most general and expensive forms embody.

The analyses which follow do not attempt to be exhaustive. The class of filters examined is restricted to those which operate on position measurements only. The general Kalman filter provides the starting point for the analyses. The discrete form of the filter is presented, without derivation, and from it are derived the general forms of recursive and fixed-parameter (steady-state) filters which are all included in the class of α-β(-γ) filters. The use of fixed-parameter filters eliminates the necessity of iteratively calculating new coefficients at every scan and thus greatly reduces the computational load of the filter portion of the automatic tracking system. The adaptation of the filter to changes in the tracking conditions (viz., maneuvers, measurement error, update interval) is discussed, and the means by which the steady-state filter may adjust to such changes is described. Some questions of practical filter design are treated and comments are offered on the cost/performance trade-offs of various basic forms of filter.

2. TRACK ESTIMATION

The role of an automatic tracking system is to provide a sequence of best estimates of the target's position and velocity, based on the available measurements and an assumed model of the target's behaviour, without operator intervention. Powerful mathematical procedures exist with which to carry out the track-estimation operations. The Kalman filter is the most general solution of the recursive, linear, mean-square estimation problem. It can be expressed in matrix notation, in a form which is very convenient for computer implementation.

2.1 Kalman Filter

The general form of the filter is described by the following equations:

Target Model
$$X_{k+1} = \Phi_k X_k + \Gamma_k U_k \quad (1)$$

Measurement Model
$$Y_k = M_k X_k + V_k \quad (2)$$

Forecast
$$X'_k = \Phi_{k-1}\hat{X}_{k-1} \quad (3)$$

$$P'_k = \Phi_{k-1}\hat{P}_{k-1}\Phi^t_{k-1} + \Gamma_{k-1}Q_{k-1}\Gamma^t_{k-1} \quad (4)$$

Estimation
$$K_{k(opt)} = P'_k M^t_k (M_k P'_k M^t_k + R_k)^{-1} \quad (5)$$

$$\hat{X}_k = X'_k - K_{k(opt)}(M_k X'_k - Y_k) \quad (6)$$

$$\hat{P}_k = P'_k - K_{k(opt)} M_k P'_k \quad (7)$$

The sampling instants at which measurements are taken and to which computed quantities apply are indicated by the k-subscripts. Forecasts and estimates are denoted by (') and (^) respectively. The superscript (t) denotes matrix transposition and the superscript (-1) denotes matrix inversion.

- X_k is the state vector of the target in track, at the k^{th} instant; P_k is its covariance matrix.
- U_k is a noise vector representing zero-mean random activity (model uncertainty); covariance Q_k.
- V_k is a noise vector representing zero-mean random activity (measurement uncertainty); covariance R_k.
- Γ_k is the excitation or maneuver matrix which specifies the effect of U_k on X_k.
- Φ_k is the state transition matrix derived from the assumed model of the dynamical behaviour of the target.
- Y_k is the observation vector of the target in track.
- M_k is the measurement or selection matrix which relates Y_k to X_k.
- $K_{k(opt)}$ is the optimum gain matrix for the determination of the estimates $\hat{X}_k$ and $\hat{P}_k$.

Kalman filtering (equations (3)-(7) inclusive) combines a track forecast, which is derived from the previous best estimate in accordance with the equations of motion, with the most recent physical measurement to produce a weighted mean, the weighting factor K being chosen to minimize the variance. For strict optimality, the noise statistics must be Gaussian, and the noise terms must be uncorrelated from one sampling instant to the next. Because it provides for the inclusion of all possible couplings of covariance terms in its matrix formulation, the Kalman filter is independent of the coordinate system in which the state variables and measurement variables are expressed.

The drawback of the Kalman filter is its computational cost. The recursive procedures require, at each sampling instant and for each target, the multiplication of matrices of order nxn and the inversion of a matrix of order mxm (see equations (4) and (5); n is the length of the state vector X and m is the length of the observation vector Y). For a track-while-scan surveillance radar system, which may be required to track many targets simultaneously, this computational load could become prohibitive, particularly when one must take into account the additional load of the automatic track-association procedures. By dispensing with various components of the full apparatus of the Kalman filter, one can produce simpler approximations to the solution of the estimation problem, with corresponding reductions in computer loading. This must be accomplished, of course, without degrading the overall tracking performance of the system to an unacceptable degree.

2.2 Simplification

There are two approaches to the simplification of the filtering procedures. The first is to break down the general matrix formulation to such an extent that it may be replaced by a small number of algebraic recursion relations. The necessary simplifying assumptions include the elimination of coordinate interaction terms in the covariance expressions, the reduction in the size of the state and measurement vectors with a corresponding reduction in the dimensions of the associated matrices, and the adoption of simple linear equations of motion derived from the transition matrix Φ (assumed invariant with k) and based on a constant sampling interval T. This results in a sub-optimal form of solution to the estimation problem often called the α-β filter. The scalar weights α and β replace the gain matrix K as coefficients in the position and velocity estimation procedure for each orthogonal coordinate of the target's motion. Because of this decoupling, the choice of coordinate system in which to express the state and measurement variables can affect the filter performance. The filter does not propagate all possible covariance terms, as does the Kalman filter.

The second approach is to adopt a constant gain K_∞ in place of the recursively computed $K_{k(opt)}$ in the Kalman filter, using invariant forms for Φ, Γ, and M. This eliminates the need for iteratively computing the covariance matrix $\hat{P}_k$, during track updating. K_∞ is the steady-state gain or limiting value of

$K_{k(opt)}$, with known or assumed values for the noise covariances Q and R. It is precomputed by iteration of the equations (4), (5) and (7) with an initial value for $\hat{P}_0$ and is subsequently applied to the sequence of target observations using only equations (3) and (6) of the tracking filter. This form of solution to the estimation problem is sometimes called the Wiener filter.

These two approaches may be combined to form a constant-gain α-β filter. This type of filter will be examined in detail in the subsequent sections.

2.3 Adaptive Filtering

Whatever method is adopted for track filtering, it is usually necessary to combine it with some form of adaptation. An adaptive system is one which continually adjusts its own parameters in the course of time to meet a certain performance criterion. By this definition neither the recursive nor the steady-state filters outlined above can be termed adaptive. For the former, the sequence of values for the gain K_k could be computed off-line and stored prior to being applied to a sequence of target observations, given a set of initial values for the covariance terms.

On-line adaptation is required when significant changes occur in the target motion (maneuvers), measurement accuracy or frequency of detection. The excitation noise covariance Q is a statistical quantity intended to cover uncertainties in the model of target motion described by Φ and Γ. Measurement accuracy is described statistically by the noise covariance R, and the interval between filter updates is given by the time T (which appears in Φ and Γ). Changes in the tracking environment must be reflected in the appropriate adjustment of these three filter parameters during the track-estimation process. Adaptive tracking requires the on-line computation of a figure-of-merit term, or track-performance indicator, which typically involves a weighted combination of the terms in the residual MX'-Y (see equation (6)). It also requires a practical procedure for determining what quantitative adjustment should be made in the filter parameters. These requirements are considered in the analyses that follow.

3. STEADY-STATE FILTERS

In this section we analyze the one-dimensional α-β and α-β-γ filters, as derived from the general form of the Kalman filter, and we present closed-form functional relationships which describe completely their steady-state characteristics.

3.1 α-β Filter

The standard equations for the α-β filter are obtained by substituting

$$X_k = \begin{bmatrix} x_k \\ \dot{x}_k \end{bmatrix}; \quad \Phi_k = \Phi = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}; \quad K_{k(opt)} = \begin{bmatrix} \alpha_k \\ \beta_k/T \end{bmatrix}; \quad Y_k = [y_k]; \quad M_k = M = [1 \quad 0]$$

in equations (3) and (6). This is a constant-velocity model for target motion, with only position measurements available. It is assumed that each position coordinate x in the target state vector is decoupled from the others and can be treated separately. Thus, for each coordinate, the tracking filter reduces to the following algebraic equations:

<u>Forecast</u> $$x'_k = \hat{x}_{k-1} + T\hat{\dot{x}}_{k-1}; \qquad \dot{x}'_k = \hat{\dot{x}}_{k-1} \tag{8}$$

<u>Estimation</u> $$\hat{x}_k = x'_k + \alpha_k(y_k - x'_k); \qquad \hat{\dot{x}}_k = \dot{x}'_k + \frac{\beta_k}{T}(y_k - x'_k) \tag{9}$$

where x_k is the target position, at the k^{th} instant, $\dot{x}_k$ is the target velocity, y_k is the observed (measured) target position, T is the sampling interval and α_k, β_k are the gain coefficients.

It is not necessary to propagate explicitly the state covariance terms in order to calculate the filter gain at each iteration. The decoupling of the state coordinates and the use of only position measurements simplify the Kalman recursion relations (equations (3), (4) and (7)) to the extent that the gain coefficients at the k^{th} instant may be calculated directly from the following algebraic relations:

$$D_k = 1 + \alpha_{k-1} + 2\beta_{k-1} + \delta_{k-1} \tag{10a}$$

$$\alpha_k = \frac{D_k - 1}{D_k} \tag{10b}$$

$$\beta_k = \frac{\beta_{k-1} + \delta_{k-1}}{D_k} \tag{10c}$$

$$\delta_k = \delta_{k-1} - \beta_k^2 \cdot D_k \tag{10d}$$

These assume that Q, in equation (4), is zero and that R and T are constant. We note that, for each coordinate, a state covariance matrix may be written

$$\hat{P}_k = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}_k = \begin{bmatrix} R\alpha_k & R\beta_k/T \\ R\beta_k/T & R\delta_k/T^2 \end{bmatrix} \tag{11}$$

where $P_{11(k)} = E\{x_k^2\}$, ($E\{\cdot\}$ denotes statistical expectation)

$$P_{12(k)} = P_{21(k)} = E\{x_k\dot{x}_k\} \simeq E\left\{x_k \cdot \frac{(x_k - x_{k-1})}{T}\right\} \simeq \frac{1}{T}E\{x_k^2\},$$

$$P_{22(k)} = E\{\dot{x}_k^2\} = \frac{1}{T^2}E\{(x_k - x_{k-1})^2\} \simeq \frac{1}{T^2}(E\{x_k^2\} + E\{x_{k-1}^2\}) \simeq \frac{2}{T^2}E\{x_k^2\},$$ assuming that x_k, x_{k-1} are statistically uncorrelated.

An explicit value for R for each target coordinate is not required. Since R is the variance in a measurement of target position ($R = E\{y_k^2\} = r$, a scalar quantity) we may also define it to be the a priori uncer-

tainty of the target position at the initiation of the tracking filter (i.e., $p_{11(o)} = r$). This assignment leads to a set of initial values for the filter gain coefficients, $\alpha_o = 1$, $\beta_o = 1$, and $\delta_o = 2$. From equation (10), the coefficients α_k, β_k both approach zero asymptotically with increasing k, as the filter relies more and more on its own forecast and subsequent measurements receive progressively less weight in the estimation.

It is possible to simplify equation (10) still further and obtain explicit expressions for α_k, β_k as functions of the iteration number k. For instance, with α_o, β_o and δ_o taking on the numerical values quoted above we find that

$$\alpha_k = \frac{2(2k+3)}{(k+2)(k+3)}; \quad \beta_k = \frac{6}{(k+2)(k+3)}; \quad \text{and} \quad \delta_k = \frac{12}{(k+1)(k+2)(k+3)} \tag{12}$$

(Equation (12c) is unnecessary for the actual operation of the filter.)

3.1.1 Random-velocity models

In radar target tracking one would not permit α and β to decrease to zero, recognizing the need to provide for some uncertainty in the target model. An alternative form of α-β filter includes this model uncertainty directly by providing for a non-zero Q. In equation (1) let U_k be a zero-mean random variable in velocity and Q_k, its covariance, be a scalar quantity q_v for each coordinate. The effect of this random velocity is included in the track-estimation process by means of the excitation matrix $\Gamma = (0 \;\; 1)^t$, and serves to allow for target maneuvers. The only change in the recursion relations (10) is the following:

$$\delta_k = \delta_{k-1} + \phi_1 - \beta_k^2 D_k \tag{10d'}$$

where $\phi_1 = q_v T^2/r$.

The filter achieves a steady state with non-zero values for α, β and δ which are independent of the initial state of the filter $(\alpha_o, \beta_o, \delta_o)$ and depend only on the system parameter ϕ_1. The transient behaviour of the filter does depend on the initial state.

As a modification to this form of filter, a different excitation matrix $\Gamma = (T \;\; 1)^t$ allows the random velocity variable to influence target position as well. The recursion relations must be rewritten as follows:

$$D_k = 1 + \alpha_{k-1} + 2\beta_{k-1} + \delta_{k-1} + \phi_1 \tag{13a}$$

$$\alpha_k = \frac{D_k - 1}{D_k} \tag{13b)=(10b}$$

$$\beta_k = \frac{\beta_{k-1} + \delta_{k-1} + \phi_1}{D_k} \tag{13c}$$

$$\delta_k = \delta_{k-1} + \phi_1 - \beta_k^2 D_k \tag{13d)=(10d'}$$

The transient behaviour differs slightly from that of the preceding filter, but the final values for the coefficients again depend only on ϕ_1.

3.1.2 Adaptation

Equations (10) and (13) retain all the features of the original matrix formulation of the Kalman filter (equations (3)-(4)) with the restrictions that (i) only target position is measured, (ii) only position and velocity are estimated, and with the assumption that target coordinates can be decoupled and treated separately. When changes in Q, R or T occur, the Kalman filter incorporates them directly, from one iteration to the next, in its recursion equations. Normal operation of an α-β filter assumes constant values for q_v, r and T, but on-line adaptation to changes in these terms can be accommodated nevertheless. If filter adaptation is required between iterations (k-1) and (k), the coefficients α_{k-1}, β_{k-1}, δ_{k-1} in equations (10) or (13) are replaced by the coefficients

$$\alpha'_{k-1} = \left(\frac{r}{r'}\right)\alpha_{k-1}, \quad \beta'_{k-1} = \left(\frac{r}{r'}\right)\left(\frac{T'}{T}\right)\beta_{k-1}, \quad \delta'_{k-1} = \left(\frac{r}{r'}\right)\left(\frac{T'}{T}\right)^2\delta_{k-1}, \tag{14}$$

and the system parameter is recomputed: $\phi'_1 = q'_v(T')^2/r'$. The coefficients α_k, β_k and δ_k are then obtained from the equations as usual. The superscript (') denotes the new or adapted values of the terms in question.

3.1.3 Steady-state analysis

To simplify this α-β filter still further, one can eliminate the iterative computation of the filter coefficients by using the steady-state (S.S.) values appropriate to the current value of the system parameter ϕ_1. Only when ϕ_1 changes during the course of the tracking operation are the filter coefficients recalculated, and then once only, for all subsequent sampling instants, or until ϕ_1 changes again. The analysis leading to the closed-form solution for $(\alpha,\beta)_{s.s.}$ as functions of ϕ_1 is outlined below.

For the recursive filter, it has been shown (Casti, 1975) that the number n(n+1)/2 of simultaneous equations that must generally be solved to obtain the steady-state gain matrix (where n is the size of the state vector), can be reduced to (np) simultaneous equations (where p is the size of the measurement vector), when p < (n+1)/2. For the α-β filter described by equation (13), with a state vector of length 2 (position and velocity), we expect initially to have to solve three simultaneous, quadratically nonlinear equations. These equations are obtained by imposing the steady-state conditions $\alpha_k = \alpha_{k-1} = \alpha$, etc. and substituting in equation (13). Then

$$\alpha(\alpha + 2\beta + \delta + \phi_1) = 2\beta + \delta + \phi_1 \tag{15a}$$

$$\beta(\alpha + 2\beta + \delta + \phi_1) = \delta + \phi_1 \tag{15b}$$

$$\phi_1(1 + \alpha + 2\beta + \delta + \phi_1) = (\beta + \delta + \phi_1) \tag{15c}$$

These can be reduced to two simultaneous equations, since p=1 (position), with the following result:

$$\beta^2 = \phi_1(1-\alpha) \quad (16) \qquad \alpha(\alpha+\beta) = 2\beta \quad (17)$$

Equations (16) and (17) form the reduced set of simultaneous quadratically nonlinear equations. Equations (17), first obtained by Benedict and Bordner (1962) and usually appearing in its alternative form as $\beta = \alpha^2/(2-\alpha)$, has often been quoted as an optimal design criterion for steady-state α-β filters. It specifies how the "optimal damping factor" β depends on the "system bandwidth" α, for all values of α. The original analysis left open the specification of α, a free parameter to be selected depending on the application. Equation (16) extends this analysis to provide the optimal specification of α as well, in terms of the global parameter ϕ_1. The same equations would result from an analysis commencing with equations (10).

Combining equations (16) and (17) we obtain a linear quartic equation

$$\beta^4 - \phi_1\beta^3 - 2\phi_1\beta^2 - \phi_1^2\beta + \phi_1^2 = 0 \qquad (18)$$

which may be solved by standard algebraic techniques. With the constraints that α and β must always be ≥ 0, and that $\alpha \leq 1$, the following unique solution is obtained:

$$\alpha = \frac{\phi_1}{8}\left\{1+\sqrt{1+\frac{16}{\phi_1}}\right\}\left\{\sqrt{2\left\{1+\sqrt{1+\frac{16}{\phi_1}}\right\}} - 2\right\}; \qquad \beta = \frac{\phi_1}{8}\sqrt{2\left\{1+\sqrt{1+\frac{16}{\phi_1}}\right\}}\left\{\sqrt{2\left\{1+\sqrt{1+\frac{16}{\phi_1}}\right\}} - 2\right\} \quad (19)$$

In the limit, as $\phi_1 \to 0$, α and $\beta \to 0$ jointly. Also, as $\phi_1 \to \infty$, α and $\beta \to 1$.

These expressions determine the optimal filtering coefficients of a steady-state α-β tracking filter for a system specified by the dimensionless parameter $\phi_1 = q_v T^2/r$, where target maneuvers are described statistically by an additive zero-mean random velocity with covariance q_v. These expressions enable the steady-state filter to adapt immediately to any change in the parameters q_v, r, or T. Values of α and β are computed using equation (19) only at track initiation, or when ϕ_1 changes during track life. Otherwise, only equations (8) and (9) are needed for track updating at each observation interval.

3.1.4 Random-acceleration model

An alternative to the velocity model is one which assumes U_k in equation (1) to be a zero-mean random acceleration with a covariance $Q = q_a$ (a scalar quantity), which is coupled into the filter equations by means of the excitation matrix $\Gamma = (T^2/2, T)^t$. The following recursion relations for this α-β filter are obtained, for each coordinate of the target:

$$D_k = 1 + \alpha_{k-1} + 2\beta_{k-1} + \delta_{k-1} + \phi_2 \quad (20a) \qquad \alpha_k = \frac{D_k - 1}{D_k} \quad (20b)$$

$$\beta_k = \frac{\beta_{k-1} + \delta_{k-1} + 2\phi_2}{D_k} \quad (20c) \qquad \delta_k = \delta_{k-1} + 4\phi_2 - \beta_k^2 D_k \quad (20d)$$

where $\phi_2 = q_a T^4/4r$, with T and r as defined previously. The closed-form solution to the corresponding steady-state filter is obtained in similar fashion as before. First we write the three simultaneous nonlinear equations:

$$\alpha(\alpha + 2\beta + \delta + \phi_2) = 2\beta + \delta + \phi_2 \qquad (21a)$$

$$\beta(\alpha + 2\beta + \delta + \phi_2) = \delta + 2\phi_2 \qquad (21b)$$

$$4\phi_2(1 + \alpha + 2\beta + \delta + \phi_2) = (\beta + \delta + 2\phi_2)^2 \qquad (21c)$$

Then we reduce these to a set of two simultaneous nonlinear equations:

$$\beta^2 = 4\phi_2(1-\alpha) \quad (22) \qquad \text{and} \qquad (\alpha + \beta/2)^2 = 2\beta \quad (23)$$

Equation (23) has appeared in the literature (e.g., Wold et al, 1972) in the form $\alpha = \sqrt{2\beta} - \beta/2$, defining the optimal α-β relationship for this filter model. Again the specification of one of the coefficients was left open. With the addition of equation (22) the optimal specification of both coefficients is obtainable in terms of the system parameter ϕ_2. Solving (22) and (23) we first obtain the quartic equation:

$$\beta^4 - 4\phi_2\beta^3 + (4\phi_2^2 - 8\phi_2)\beta^2 - 16\phi_2^2\beta + 16\phi_2^2 = 0 \qquad (24)$$

which may be solved by standard procedures. With the same system constraints as before ($\alpha,\beta > 0$, $\alpha \leq 1$) the following unique solution is obtained:

$$\alpha = \frac{1}{2}\sqrt{\phi_2 + 4\sqrt{\phi_2}}\left\{\sqrt{\phi_2} + 2 - \sqrt{\phi_2 + 4\sqrt{\phi_2}}\right\}; \qquad \beta = \sqrt{\phi_2}\left\{\sqrt{\phi_2} + 2 - \sqrt{\phi_2 + 4\sqrt{\phi_2}}\right\} \qquad (25)$$

In the limit, as $\phi_2 \to 0$, α and $\beta \to 0$ jointly. Also as $\phi_2 \to \infty$, $\alpha \to 1$ and $\beta \to 2$.

This result (equation (25)) is equivalent to one obtained previously by Friedland (1973), which was cast in a different form.

It is possible to extend these analyses to a filter model in which target maneuvers are covered statistically by an additive zero-mean random "jerk" (rate of change of acceleration) with covariance q_j. Similar results are obtained, but their description will be omitted here.

3.1.5 Summary

This completes the theoretical treatment of α-β tracking filters. The relationship to the more

general Kalman filter has been shown and the general recursive behaviour has been described. Two different models for target maneuver were treated. The recursion relationships have led to analyses of the steady-state filter and closed-form solutions for the optimal filtering coefficients were obtained for each case. These studies in steady-state tracking filters have brought together earlier results hitherto unconnected. They have also demonstrated the possibility of using steady-state adaptive filters, which avoid the necessity of computing updated coefficients at every observation interval, while approaching near-optimal performance.

3.2 The α-β-γ Filter

The natural extension of the α-β filter is one which includes target acceleration as an explicit term in the state vector. The resulting α-β-γ filter models a constant-acceleration target, with measurements made only on target position. Again it is assumed that each coordinate can be treated separately. We substitute in equations (3) and (4):

$$x_k = \begin{bmatrix} x_k \\ \dot{x}_k \\ \ddot{x}_k \end{bmatrix}; \quad \Phi_k = \Phi = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix}; \quad K_{(opt)k} = \begin{bmatrix} \alpha_k \\ \beta_k/T \\ \gamma_k/T^2 \end{bmatrix}; \quad Y_k = [y_k]; \quad M_k = M = [1 \;\; 0 \;\; 0]$$

to obtain the following algebraic equations:

<u>Forecast</u>
$$x'_k = \hat{x}_{k-1} + T\hat{\dot{x}}_{k-1} + T^2\hat{\ddot{x}}_{k-1}/2; \quad \dot{x}'_k = \hat{\dot{x}}_{k-1} + T\hat{\ddot{x}}_{k-1}; \quad \ddot{x}'_k = \hat{\ddot{x}}_{k-1} \tag{26}$$

<u>Estimation</u>
$$\hat{x}_k = x'_k + \alpha_k(y_k - x'_k); \quad \hat{\dot{x}}_k = \dot{x}'_k + \frac{\beta_k}{T}(y_k - x'_k); \quad \hat{\ddot{x}}_k = \ddot{x}'_k + \frac{\gamma_k}{T^2}(y_k - x'_k) \tag{27}$$

where $\ddot{x}_k$ is the target acceleration, γ_k is the acceleration coefficient of the tracking filter, and all other terms are as defined in Section 3.1.

Under the assumption of an accurate model for target motion (Q=0), the filter coefficients are obtained at each observation instant, for constant T, by means of the following set of recursion equations:

$$\alpha_k = \frac{D_k - 1}{D_k} \tag{28a}$$

$$\beta_k = \frac{\beta_{k-1} + \gamma_{k-1} + \delta_{k-1} + (3\varepsilon_{k-1} + \eta_{k-1})/2}{D_k} \tag{28b}$$

$$\gamma_k = \frac{\gamma_{k-1} + \varepsilon_{k-1} + \eta_{k-1}/2}{D_k} \tag{28c}$$

$$\delta_k = \delta_{k-1} + 2\varepsilon_{k-1} + \eta_{k-1} - \beta_k^2 D_k \tag{28d}$$

$$\varepsilon_k = \varepsilon_{k-1} + \eta_{k-1} - \beta_k\gamma_k D_k \tag{28e}$$

$$\eta_k = \eta_{k-1} - \gamma_k^2 D_k \tag{28f}$$

where

$$D_k = 1 + \alpha_{k-1} + 2\beta_{k-1} + \gamma_{k-1} + \delta_{k-1} + \varepsilon_{k-1} + \eta_{k-1}/4. \tag{28g}$$

For given values of $(\alpha_o, \beta_o, \gamma_o, \delta_o, \varepsilon_o, \eta_o)$ explicit formulae in k for each of the filter coefficients have been obtained by the author from a lengthy numerical analysis resulting in very cumbersome expressions (ratios of polynomials up to 9^{th} order). These formulae are not useful for practical filter design and are omitted here.

3.2.1 Random-acceleration model

Analogous to the development of the α-β filter, the simplest means of introducing a target maneuver compensation would be by means of a zero-mean random acceleration term U_k with covariance Q_k coupled into the general filter equations (1) and (4) via the excitation matrix $= (0\;0\;1)^t$. This would result in a set of equations (28') identical to the set (28) except for

$$\eta_k = \eta_{k-1} + \phi_3 - \gamma_k^2 \cdot D_k \tag{28f'}$$

where $\phi_3 = q_a T^4/r$, and q_a, r and T are as defined in Section 3.1.4. Alternatively, the excitation matrix $\Gamma = (T^2/2,\ T,\ 1)^t$ may be used, which yields the similar set of equations, differing slightly in detail. These two models produce very similar α-β-γ filters which display slightly different transient behaviour but which reach identical steady-state values. The six coefficients indicated are derived from the independent terms of the covariance matrix P (see the general Kalman equations (3) through (7)).

3.2.2 Adaptation

The inclusion of adaptive features in this recursive α-β-γ filter, when q_a, r and T are subject to change during the life of the track, is exactly analogous to the case for the α-β filter (see Section 3.1.4).

3.2.3 Steady-state analysis

The steady-state values of the filter coefficients α, β, and γ, can be calculated in closed form as a function of the system parameter ϕ_3. Since the length of the state vector is n=3, we expect n(n+1)/2=6 simultaneous equations to solve for the steady-state coefficients. These correspond to the six unknowns, represented by the coefficients α, β, γ, δ, ε, η. However, since the length of the observation vector is p=1, it is sufficient to solve a reduced set of np=3 equations, which correspond to the three essential coefficients of the α-β-γ tracking filter. Setting $\alpha_{k+1} = \alpha_k = \alpha$, etc. in equation (28'), the resulting six simultaneous, quadratically nonlinear equations are reduced to the following set of three equations:

$$\gamma^2 = \phi_3(1-\alpha) \tag{29}$$

$$\beta^2 = 2\alpha\gamma \tag{30}$$

$$\alpha(\alpha+\beta+\gamma/2) = 2\beta \tag{31}$$

Equations (29), (30), and (31) form the reduced set of simultaneous quadratically nonlinear equations which fully characterize the steady-state α-β-γ filter. Equation (31) was first obtained by Simpson (1963) as a result of numerical analyses extending the original work of Benedict and Bordner on α-β filters. Equation (30) was later presented along with equation (31) by Neal (1967) as a result of an analysis of a Kalman filter model with a Gauss-Markov random-acceleration model. Neal's result leaves one free parameter to be specified by the specific application. The analysis presented here derives equation (29) as well, and completes the specification of the filter as a function of a single system parameter ϕ_3.

The closed-form solution of the reduced set is less straightforward than in the cases described in Section 2. The reduced set of three simultaneous equations produces one sextic polynomial equation which is not generally soluble. Without a specific factorization to render it soluble, a more circuitous method must be used. By combining equations (30) and (31) the relationship $(\alpha+\beta/2)^2 = 2\beta$ is obtained (Neal also noted this relationship in the equivalent form $(2\alpha+\beta)^2 = 8\beta$)), identical to that for the random-acceleration model for the α-β filter (equation (23). The closed-form solution of equation (25) may now be used by determining the correspondence between ϕ_3 and ϕ_2. From equations (25), (29) and (30), this correspondence may be expressed by

$$\phi_3 = \frac{4\phi_2^2}{\phi_2 + 4\sqrt{\phi_2}} \; . \tag{32}$$

Rewriting this equation as a cubic polynomial and solving for ϕ_2 explicitly yields

$$\begin{aligned}\phi_2 &= \frac{\phi_3}{6}\left[1 - \frac{1}{2}\left\{\sqrt[3]{1 - \frac{864}{\phi_3}\left[1 + \sqrt{1 - \frac{\phi_3}{432}}\right]} + \sqrt[3]{1 - \frac{864}{\phi_3}\left[1 - \sqrt{1 - \frac{\phi_3}{432}}\right]}\right\}\right], \quad \text{for} \quad \phi_3 \le 432; \\ &= \frac{\phi_3}{6}, \quad \text{for } \phi_3 = 432; \quad = \frac{\phi_3}{6}\left[1 + \cos\left\{\frac{1}{3}\cos^{-1}\left(\frac{864}{\phi_3} - 1\right)\right\}\right], \quad \text{for } \phi_3 \ge 432.\end{aligned} \tag{33}$$

For a given value of system parameter ϕ_3, a corresponding value of ϕ_2 is computed by means of equation (33). Explicit values of α, β and γ are then computed from equations (25) and (30).

The solution for the steady-state filter was obtained through the happy occurrence of an identical functional relationship between the coefficients α and β for both the second-order (α-β) filter and third-order (α-β-γ) filter when the same model for a random-acceleration perturbation on the target is included. This does not mean that the two filters are identical in other respects, in spite of the fact that their respective global parameters ϕ_2 and ϕ_3 have similar structures. For matching values of q_a, r and T (identical system specifications) the resulting value for $\phi_3 = q_aT^4/r$ in the case of the third-order filter will in turn produce a corresponding value of ϕ_2 which is not the same as that which would be obtained for the second-order filter from $\phi_2 = q_aT^4/4r$. Therefore, the respective coefficients α and β in the two cases would not correspond, and the filters would differ in behaviour.

The use of the third-order steady-state filter in an adaptive fashion follows analogously from the description given at the end of Section 3.1.3, and the new closed-form solution for the optimal steady-state condition can contribute to its implementation. However, their close interrelationship suggests the possibility that in a practical system, the track-estimation operation could be switched back and forth between a second-order and a third-order filter depending on the current behaviour of the target. The second-order filter is better suited to producing smoothed estimates of a constant-velocity (straight-line) target track while the third-order filter can better handle a constant-acceleration (turning) target.

4. FILTER DESIGN

We now look at various approaches to the implementation of tracking filters. No attempt is made at complete designs but some of the implications of the foregoing analyses are examined from the point of view of a designer of an air-surveillance radar-tracking system.

4.1 Filter Categories

Tracking filters may be classified under a number of headings, the most common being:

(a) Recursive and steady-state (fixed-parameter);

(b) Adaptive and non-adaptive;

(c) Coupled and decoupled coordinates (a third category: "combined" coordinates should be included);

(d) Third and second order (the two most often adopted, although first order or higher-than-third order filters are possible);

(e) Three-dimensional and two-dimensional (depending on the radar sensors).

The category mentioned first in each listed item is the more computationally complex.

4.2 Filter Initialization

When a new target track is acquired, a smoothing and prediction filter is initialized for that track. An estimate of the state of the target is made - position and velocity (for a second-order filter), and acceleration (added, for a third-order filter). From a knowledge of the characteristics of the radar sensor and the signal-processing and plot-detection operations, a suitable estimate for the measurement covariance R is determined. With the assumption of a particular model for target dynamics to be employed by the filter and an estimation of the maneuvering abilities of the class of targets to be tracked, an a priori specification of the model uncertainty covariance Q is made. Finally, with the inclusion of the update interval T, the tracking filter is initialized to carry out smoothing and prediction on subsequent measurements of track position.

In the recursive, coupled (i.e., Kalman) filter we use the full matrix specification for R and Q. In the decoupled (i.e., α-β($-\gamma$)) filter, both recursive and steady-state, we select specific elements of R and Q to compute the appropriate system parameter for each coordinate. In the combined filter, we extract a single scalar value from each of R and Q (i.e., a combination of the separate elements of each) to compute a single system parameter applicable to all coordinates of target position.

4.3 Coordinate Transformations

The radar sensor measures target position in a line-of-sight coordinate frame (i.e., the polar coordinates of range, azimuth, and possibly elevation angle). However, the filtering of track data in these coordinates can lead to large dynamic errors when a linear model for target motion is used, as in the formulations described in the preceding sections. Simple constant-velocity target tracks appear nonlinear in these coordinates, and artificial acceleration components are generated. This problem does not arise if track filtering is done in a fixed Cartesian reference frame. It is generally desirable to use fixed (earth-referenced) Cartesian coordinates for TWS filtering, particularly when one must consider distributed multi-sensor surveillance systems and the problem of track registration. However, the use of decoupled coordinates, as required by the recursive or steady-state forms of the α-β($-\gamma$) filter, is only strictly valid in a line-of-sight coordinate system, for which the component measurement-errors are independent. The fully-coupled Kalman filter, operating in fixed Cartesian coordinates, absorbs the resulting cross-terms in the measurement covariance matrix R directly. A decoupled filter ignores them from the outset. The difficulty can be overcome, if desired, by the inclusion of suitable coordinate transformations in the filter operation. The required procedures are reviewed below.

4.3.1 Measurement covariance

Consider a simple two-dimensional tracking situation. The target position is measured in terms of range ρ and azimith θ, and may be expressed in fixed Cartesian coordinates $x_1 = \rho\cos\theta$, $x_2 = \rho\sin\theta$. The measurement covariance in polar coordinates is $R(\rho,\theta) = \begin{pmatrix} \sigma_\rho^2 & 0 \\ 0 & \sigma_\theta^2 \end{pmatrix} = \begin{pmatrix} r_\rho & 0 \\ 0 & r_\theta \end{pmatrix}$ expressed in matrix form.

Then in Cartesian coordinates the covariance is

$$R(x_1,x_2) = F(\rho,\theta)R(\rho,\theta)F^t(\rho,\theta) \tag{34}$$

where

$$F(\rho,\theta) = \begin{pmatrix} \partial x_1/\partial\rho & \partial x_1/\partial\theta \\ \partial x_2/\partial\rho & \partial x_2/\partial\theta \end{pmatrix} = \begin{pmatrix} \cos\theta & -\rho\sin\theta \\ \sin\theta & \rho\cos\theta \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\cdot\begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix} = A(\theta)\cdot S(\rho) \tag{35}$$

(ref. Spingarn and Weidemann (1972)). It is useful to note that: i) $A(\theta)$ is orthogonal and $A^t = A^{-1}$; and ii) $S(\rho)$ is diagonal and the computation of S^{-1} is trivial. The matrix A defines a clockwise rotational transformation between two systems of orthogonal coordinates. A counter-clockwise rotation would be defined by A^t.

For the Kalman filter, tracking in fixed Cartesian coordinates is most common and equation (34) would be employed. Suppose instead that Cartesian coordinates (u_1,u_2) are oriented along the line-of-sight from sensor to target. The errors in position measurement in this frame are then independent, with covariance

$$R(u_1,u_2) = \begin{bmatrix} r_{u_1} & 0 \\ 0 & r_{u_2} \end{bmatrix} = \begin{bmatrix} \sigma_\rho^2 & 0 \\ 0 & (\rho\sigma_\theta)^2 \end{bmatrix} \tag{36}$$

For the decoupled filter each diagonal element in equation (36) would be used in the calculation of the system parameter corresponding to its coordinate. For the combined filter, a single term r would be used, determined by, say, the maximal or average value of r_{u_1} and r_{u_2}.

In three dimensions, analogous expressions are obtained.

4.3.2 Model uncertainty covariance

If there is no specific directionality associated with unmodelled target maneuvers (represented by zero-mean random velocity or acceleration), a simple assumption is to let Q be a diagonal matrix qI_2, for the example of a two-dimensional filter. Here, q is a scalar variance in velocity or acceleration, and I_2 unit matrix of order 2.

Refinement of this specification is possible. The target direction (velocity) is known, approximately, from the track initialization, and the angle θ_1 between the track-oriented coordinates defined by it and the coordinates of the filter may be calculated. Since it is more likely that target maneuvers will take the form of turns than of changes in velocity along the current line of travel, an empirical weighting may be assigned to "across-track" (W_{ac}) and "along track" (W_{al}) random maneuvers. This weighting may then be transformed into line-of-sight coordinates (u_1,u_2) by means of the rotation $A(\theta_1)$ in equation (37), from which the specification for Q in equation (38) is obtained.

$$\begin{bmatrix} W_{u_1} \\ W_{u_2} \end{bmatrix} = A(\theta_1)\cdot\begin{bmatrix} W_{al} \\ W_{ac} \end{bmatrix} \tag{37}$$

$$Q = \frac{1}{|W_{u_1}|+|W_{u_2}|}\begin{bmatrix} |W_{u_1}|q & 0 \\ 0 & |W_{u_2}|q \end{bmatrix} \tag{38}$$

The diagonal element specification of Q could apply to the Kalman filter (in fixed coordinates) as well as to the decoupled α-β filter. In the latter, each diagonal element contributes to the determination of the system parameter corresponding to its coordinate. For the combined α-β filter, only the quantity q would be used.

4.3.3 Filter gain

In line-of-sight coordinates, the computation of the gain coefficients produces the same result in both the fully-coupled Kalman filter and the decoupled α-β(-γ) filter. The following array of terms appears (equation (39)):

The terms represent either the recursive values, to be recomputed at each iteration of the filter, or steady-state values obtained as functions of the system parameters of each coordinate, in accordance with the formulae presented in Sections 2 and 3.

$$K(L.O.S.) = \begin{bmatrix} \alpha_{u_1} & 0 \\ \beta_{u_1}/T & 0 \\ (\gamma_{u_1}/T^2) & 0 \\ 0 & \alpha_{u_2} \\ 0 & \beta_{u_2}/T \\ 0 & (\gamma_{u_2}/T^2) \end{bmatrix} \quad (39)$$

The rotation of this gain matrix through an angle θ into the fixed Cartesian coordinate frame is carried out by means of the equation

$$K(F.C.) = [A(\theta) \otimes I_N] \cdot K(L.O.S.) \cdot A^t(\theta) \quad (40)$$

where I_N is the unit matrix of order N, the order of the filter, and $\otimes$ represents the Kronecker-product operation, which is non-commutative and of higher precedence than the inner-product operation. Equation (40) is a re-statement, in a notationally compact form, of a result presented and numerically verified by Castella and Dunnebacke (1974). The matrix K(F.C.) would then be used in equation (6) to produce track smoothing.

This technique is an alternative to the computation of the gain matrix directly in fixed coordinates using the fully-coupled matrix formulation of the Kalman filter. It allows the decoupled form of filter to be used without loss of generality. It may be applied to both recursive and steady-state versions of the tracking filter. The extension to three-dimensional tracking is straightforward (see Ramachandra and Srinivasan (1977)).

In the case of the combined-coordinate filter, of course, the technique does not apply, since the computation of gain coefficients is intentionally collapsed into one dimension.

4.4 Filter Adaptation

The adaptation of recursive tracking filters to changes in the environmental parameters Q, R and T has been discussed in Section 3.1.2. For the class of optimal steady-state filters developed in this paper, it is only required to recalculate the relevant global system parameter, which in turn determines the new gain coefficients to be applied. Changes in R (brought about by a significant change in the position of the target-in-track with respect to the origin of the tracking coordinates) and T (brought about by missed plots on individual scans, or by asynchronous combining of reports on one target from several sensors) will occur as a matter of course during the life of the track and are easily identified. To determine whether a change in Q is necessary, some form of maneuver detector is required.

Referring to equations (5) and (6), the track residual (MX'-Y) has a covariance $Z = (MP'M^t+R)$. The normalized squared residual, a scalar quantity, $NSR = (MX'-Y)^t(Z^{-1})(MX'-Y)$, is often used as an on-line measure of track quality. When this figure is found to be consistently (that is, for two or three consecutive updates) greater than some upper threshold or less than some lower threshold, it indicates that an alteration in the size of the elements of Q should be made. Otherwise, the filter is well adapted to the maneuver characteristics of the target. The choice of the threshold values is a matter of designer's judgement. Note that if the residual may be assumed multi-variate-normal-distributed, then NSR will be χ^2-distributed. The rescaling of Q typically would be proportional to the current value of NSR. At the same time, the terms of Q could be re-weighted in accordance with the current track direction, using equations (37) and (38).

For the decoupled-coordinate filter, the covariance Z of the residual is expressed by the diagonal matrix

$$Z(u_1,u_2) = \begin{bmatrix} r_{u_1}/(1-\alpha_{u_1}) & 0 \\ 0 & r_{u_2}/(1-\alpha_{u_2}) \end{bmatrix} \quad (41)$$

as computed in assumed line-of-sight coordinates. Then the NSR of the track residual determined with respect to fixed coordinates at an angle θ to the instantaneous L.O.S. coordinates is

$$NSR = [MX'-Y]^t Z^{-1}(x_1,x_2)[MX'-Y] = [MX'-Y]^t A(\theta) Z^{-1}(u_1,u_2) A^t(\theta)[MX'-Y] \quad (42)$$

For the combined-coordinate filter, the covariance is a scalar quantity $r/(1-\alpha)$ and no transformation is required.

The covariance of the residual may also be used in the track association process in the establishment of optimal "gate" sizes in the measurement space, centred on the next predicted position of the target, within which valid plots for updating the track will most likely be found.

4.5 Computation of Coefficients

In the case of constant-gain filters, when the computation of the optimal steady-state coefficients need be done only once or a small number of times over the life of the track, it would be satisfactory to carry out explicitly, as required, the rather involved calculations implied by equations (19) or (25) in

the case of second-order filters, with the addition of equation (33) when a third-order filter is used. The elimination of the need for recursive gain calculations at each update interval over all tracks results in a considerable saving of computing time.

However, with the inclusion of the adaptive feature, such filters can show a rather volatile behaviour in response to changing track conditions. A more practical and efficient approach would be to use a table-look-up procedure, reducing the computational load still further. A list of about 100 entries of α-β(-γ) coefficients against the corresponding global system parameter ϕ would be more than sufficient, considering the precision of the estimates of Q and R. If the entries of ϕ are uniformly distributed in in the table according to the logarithm of their values, the largest deviation from the correct value of gain coefficient resulting from the selection of nearest match in the list to the calculated value of ϕ would be about 2%. The table could be contained in less than 1K word of computer memory. An even greater speed advantage could be realized with the use of a small content-addressable memory unit.

5. PRELIMINARY SIMULATION EXPERIMENTS

A computer simulation has recently been developed by the author as a tool for conducting experiments in automatic tracking, including initiation, association, filtering, and man/machine interaction. The different categories of tracking filters listed in Section 4.1 are currently being tested with this facility. Some initial results have been obtained, but the conclusions that may be drawn from them are necessarily tentative and subject to correction when the full results become available.

One experiment simulated a 2-D radar tracking a single target under TWS operation. The variable parameters included the false-alarm density and the probability of detection. The output was applied to a 2-D adaptive tracker using, in turn, a fully-coupled recursive (Kalman) filter, a decoupled fixed-parameter filter and a combined-coordinate fixed-parameter filter. In each case, the same simple automatic acquisition (three consecutive "hits") and association (nearest-neighbour) procedures were used.

Under conditions of "ideal" tracking, which we define as those for which the variance of the prediction error remains less than the variance of the measurement error (i.e., when α, the gain coefficient of position, is less than 0.5), the Kalman filter gave more accurate estimates of the target motion. However, the values of the parameters Q, R, and T encountered in operational systems suggest that "non-ideal" tracking conditions are not uncommon. The simulation results indicated that under such conditions the steady-state filters provide equally good estimates and that they are therefore sufficiently accurate for surveillance applications. The number of times the track was lost in a group of trials indicated that track association was performed equally well whichever type of filter was used.

Third-order filters were found to perform better than second-order filters against highly maneuverable targets. As expected, the direct estimation of terms through acceleration reduced the incidence of track loss for such targets. The limited results so far available showed no apparent instability or tendency to poor smoothing in the third-order filters.

The expected superiority of steady-state decoupled-coordinate filter (with transformations from instantaneous L.O.S. coordinates to fixed coordinates) over the steady-state combined-coordinate filter has so far appeared only under ideal tracking conditions, when a slight improvement in track estimates was recorded. The track-oriented coefficient-weighting scheme of Section 4.3.2 has not yet been assessed.

The work performed to date leads to the conclusion that the adaptive, third-order, steady-state filter, operating in either the decoupled- or the combined-coordinate mode, is a practical option in the cost/performance trade-off for surveillance-radar trackers.

6. ACKNOWLEDGEMENT

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DISCUSSION

J.R.Moon, UK

Do your general forms of steady state α, β, γ conform to the well-known stability limits of such filters derived from the requirement for the filter poles to lie within the unit circle of the z-domain?

Author's Reply

Yes. The derivations in the paper conform to the classical stability requirements for these forms of filter.

P.R.Walywyn, UK

Has the author studied an α, β, γ filter defined by E.J.Pollock (Kirkland AFB TN228, "In Loop Integration Control")?

Author's Reply

I have not studied this particular technique. When choosing an empirical adaptive technique for the use with track estimation, one should know exactly what it is meant to do, in what set of conditions it is meant to operate. Pollock's technique appears to be very carefully tailored to deal with a tracking-radar task in which the data rate is relatively high (of the order of 10/second). The adaptation procedures discussed in this paper are intended for Track-While-Scan systems with search radars, for which data rates are at least an order of magnitude lower.

Automatic Track Initiation for a Phased Array Radar Using a Clutter Map

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SUMMARY

An automatic track initiation process will produce tracks not only from real target echos but also tracks consisting of clutter plots. In a dense clutter environment, this consumes computing power and may overload the radar data processing units. For computer controlled phased array systems, these false tracks result in a poor management of the radiated energy. In the ELRA system under construction at the FFM, a statistical method for track validation has been introduced which uses a sequential likelihood ratio test procedure. The test discriminates between tracks of the wanted objects and false tracks on the basis of the target detection probability and the local false alarm probability. The latter is estimated for each search plot in a clutter map which is a list of stored clutter echos. The map is updated in real time and the list organization technique provides a set of converging volumina containing the estimation point so that nonparametric estimates can be obtained by testing on uniformity. Core memory and computing time requirements allow real time operation in a multipurpose computer programmed in higher level language.

I. INTRODUCTION

Automatic radar data processing by computers has reached, under clutter free conditions, the performance of a well trained and nonstressed human operator looking at the raw video display. But with increasing false alarm probability, the discrimination between plots from real targets and plots produced by noise and clutter is more problematic for computer-supported systems. Under special conditions, the human capability for time dependent pattern recognition seems to be superior to the currently known algorithms of target acquisition and tracking.

An automatic track initiation procedure, taking each plot as a candidate to be a true target plot, will produce not only tracks from real target echos but also tracks consisting of false alarms due to noise and clutter. If the false alarm probability is sufficiently small, these false tracks can be cancelled. Normally tracks are terminated if the consecutive number of missing plots (no correlating echos) becomes to high. In that case, the detection probability is too small for track continuation. But in more dense clutter environments, they will be continued over longer periods of time. Under those conditions, more sophisticated techniques to detect false tracks have to be applied (van Keuk, 19?7), for instance, looking into the statistics of plot-to-track correlations. False tracks, of course, consume computing power and may overload the radar data processing units. For a computer-controlled phased array system they result, furthermore, in wasted power due to poor management of the radiated energy.

Some radar applications - for instance 3D radar in military equipments against low flying aircraft - do not allow small false alarm rates without reduction of the detection probability. In these cases, we can assume dense clutter environments to be the normal operating conditions, especially if we take into account the various kinds of man made interference.

If the number of plots from parts of the surveillance area significantly exceeds the maximum expected number of targets, the data processing units should not attempt to build up tracks from all data. If the plot set is ambiguous, the computer load will grow exponentially with increasing false alarm rate because all combinations of plots to tracks have to be checked, and the number of possibilities rises so fast that even additional computing power will be overloaded. The data processing system should be able, to filter out the false alarms by the use of additional information concerning the spatial and temporal context; it is the way a human operator would proceed. Such information can be known a priori or must be learned during operation. We can see it as a longer term accumulated decision aid in comparision to the methods applied for signal detection.

Clutter echos are often not very different from real targets in signal strength and phase distortions which occur by low elevation scanning. Therefore raising the detection threshold and further filtering will reduce the subclutter visibility of the system. A similar effect is obtained if one ignores all plots from these regions which are assumed to deliver only clutter data. This method of blanking, done by software or sometimes by hardware, can be seen as a decision with a (0,1) outcome saying which data are assumed to be false alarms. In the following it is proposed to use for the clutter-target decision a real number in the interval {0,1} defined as a probability. This allows more flexibility by adapting to the local false alarm rate. In addition this estimate can be used to improve the decision between true and false tracks (and track initiation processes) in areas of modest P_F.

II. ELRA TRACK INITIATION

The ELRA computer controlled phased array system under construction at the FFM handles tracking and searching as independent processes (van Keuk, 1975), scanning the objects being tracked with individual sampling rates. Plots from the search activity are candidates for new tracks, after they have been checked not to correlate to objects under track.

The data set of a search plot consists of spatial and further information:

r	-	Range	from the detection units
u	-	Azimuth	
v	-	Elevation	
$\dot{r}$	-	Doppler	
A	-	Amplitude	
t	-	Time	
N	-	Additional information, label etc.	
P_F	-	False alarm probability	

P_F is the probability that a search plot under consideration is a false alarm. This estimate P_F is delivered from a particular modul at the stage of data processing and comes not from the signal detection units, but is added to all search plots by the central computer before any further computations are executed. How to get this estimate for P_F by the clutter map, which is stored in the ELRA central computer, is described below. This map should be distinguished from, say, MTI maps (at the stage of signal processing) which support the plot detection in contrast to the central processor map which supports the track detection and the tracking process.

The decision on the further processing of a search plot is dependent on the P_F value; that means that those plots are rejected which are believed to be a false alarm with high probability, and that a track initiation process is started if a search plot has a low P_F value. In the latter case we have a great chance that tracking will be successful because plots from nearly noise-free and clutter-free regions are targets with high probability. On the other hand, with increasing P_F, we can more and more exclude, that the plot data refer to the position or doppler of a target. We must assume that above a certain P_F threshold a tracking algorithm will always get enough track plots, but we cannot exclude that we are tracking a random walk. Therefore search plots with P_F above the threshold are excluded from the track initiation, and regions of false alarm rates too high for tracking are blanked out.

Generally we should try to start a track initiation process if the estimated false alarm probability at the target position is smaller than the above mentioned limit derived from stability arguments. In addition we may need a lower threshold to automatically exclude computer time and energy consuming initiations during phases of high system load. This produces a graceful degradation behavior and keeps the system working for those tasks which just can be managed.

If a search plot has passed the P_F threshold, a track initiation is started and track commands are given in order to build up the track with further data. But these further track plots are received only with a certain probability. Therefore, more or less frequently, missing plots will occur, and we get a sequence of, say, m numbers relating a "one" for echo and a "zero" for missing plot
1, 0, 0, 1, 0, 1, 1, 0, 0, 1, 0, 1, 1,
with k ones, which is composed of target plots and/or clutter plots according to the target detection probability and the false alarm probability in the correlation gates. These correlation gates can be kept small in comparision to conventional rotating radar with tracking by regular scanning. If we can choose the sampling time, then it is possible to take into account the temporal growing of the correlation gates.

Since a phased array radar has the capability to send the next track command to the expected target position, with only a very short time delay, we assume that the P_F estimate

will remain unchanged in the early tracking phase. With a prespecified minimal detection probability P_{D_1} for true target tracks, we can perform a test whether the mentioned plot/no plot or zero/one sequence must be explained by a real target or represents a false track. In the ELRA system, a sequential likelihood ratio test is applied to decide between the two hypotheses

H_1: true track, a target is present,

H_0: false track, no target is present.

The test function

$$u_m = P_{D_1}^{k}(1-P_{D_1})^{m-k} / (P_F^{k}(1-P_F)^{m-k}),$$

is the ratio of the two probabilities, conditional on the two hypotheses, for the event of k plots out of m track commands. The function is updated for each track command and compared with two thresholds $h_1(m)$ and $h_0(m)$. If one of the thresholds is crossed over, the corresponding hypothesis is accepted, otherwise the test is continued.

This statistical decision method needs on the average a minimal sample size for a prespecified probability of error α, accepting H_1 if H_0 is true, and β, rejecting H_1 if it is true. The thresholds $h_1(m)$ and $h_0(m)$ are functions of α and β, and for simpler calculation the logarithms are taken as for the test function. We have only to count the number of succesful track commands and compare it with linear functions for $\bar{h}_1$ and $\bar{h}_0$ as is shown in figure 1. In (Binias, 1975), these tests for zero/one sequences are studied with respect to the average test length and the track acceptance probability P(AC) which can be derived from the operating characteristic function under various P_F conditions. Fig. 2 shows the average sample size, conditioned on the α, β and P_{D_1} parameter values given in the figure, as function of the target detection probability P_D. These parameters can be changed to modify the curves in order to meet operational requirements. Figure 3 shows the corresponding track acceptance probabilities for different P_F which has to be derived from the clutter map. We can see that the test enables initiation of true tracks in spite of small detection probabilities, if P_F is small enough. But in cases of strong clutter interference the proposed test mechanism excludes tracking of weak targets. That is reasonable because the track plots are distorted by clutter and dont represent the target motion.

After one has decided for a true track, the mentioned test function after some modification, can be further used as a current track quality parameter or possibly as a sampling time and track termination criterion.

All search plots which fail to produce a track by the described initiation procedure are regarded as false alarms and may be used for updating the clutter map which has a data basis accumulated during a learning phase. Updating also requires elimination of the old data, but we must assume only slowly changing clutter over periods, which are needed for learning. By this map we have in the central computer an empirical frequency distribution of the false alarms in the surveillance area. Normalizing for the search cell volume, we can estimate the false alarm probability for one search cell which in turn is the P_F value for a new search plot.

III. CLUTTER MAP

Clutter distributions cannot be assumed to belong to any prespecified parametric family of distribution functions, and in this context nonparametric methods of point estimation are appropriate. These methods (e.g. histograms, Kernel functions, orthogonal series, k-nearest neighbor) define a certain environmental region around the estimation point (Cover 72) in order to balance bias and variance of the estimates. These regions depend not only on the sample size, but also on the underlying density itself, leading to biased estimates Bias errors are dominant if the environment region is too large; if it is too small, the error is mainly given by the variance of estimation in consequence of the random character of the sample.

We can conclude that individual estimation in a search cell not refering to the environment yields great variances if we have a finite sample set much smaller than the number of cells in the surveillance area of a long range 3D radar. Averaging may introduce bias and will be time consuming when computed in real time.

The computing time for updating and estimation has to be smaller than the time between successive track commands for a certain target. For phased array radars this time may be very short - in the millisecond range - in contrast to rotating track while scan systems. Therefore the clutter map must be stored in the fast core memory which is usually too limited to provide one address for each search cell. Furthermore, it would take long times to accumulate a sufficient number of false plots unless most of the memory is wasted.

Appropriate search-cell associations have to be formed, but they must be very flexible according to the complicated shapes of cluttered regions and the resolution of fixed point clutter.

If we would use external storing devices like disks, the data exchange to the tracking processor requires waiting times, again in great contrast to track-while-scan systems, where it is known in advance by the regular scanning which regions are be scanned for search plots.

a.) List processing technique

Therefore list processing techniques must be applied which allow associative searching in different neighborhood volumina. All nontrivial list-organisation techniques involve some partitioning scheme of the data space, more precisely of the data key space which in our case is the space of the range, azimuth and elevation coordinates. In the following, a binary partition method is described forming subspaces for the data keys which are appropriate for estimation under the mentioned computing time and memory restrictions. The method is referred to as a TRIE (Knuth, 1973; from retrieval) list organisation and can be described by the following statement:

The data key space and further subspaces are subdivided if they contain more than one datum.

Figure 4 shows a subdivision scheme for two dimensional data spaces in four equal parts. The organisation used in our ELRA system, of course, is three dimensional and therefore not very well suited for demonstration. Additional data in a subspace give rise to further subdivision until all data have their own, certainly smaller subspace allowing direct access for retrieval. This procedure results in many possibilities to form associations of data key spaces and, if there are clusters of data the subspaces can be as small as a singular search cell. If we have in a subspace only one datum, then there is no reason to exclude a local uniform distribution, and more structure in the data distribution can be detected if additional data form a set of subspaces of some irregularity.

This data organisation can be implemented as a tree structure in the memory of the computer if we represent the subspaces by nodes of the tree. Each node has four address links which refer to further subspaces, or at the leaves of the tree they refer to the data (fig. 5). For estimation described below, the data in the corresponding subspace are counted so that the root node counts all data in the list. By this technique the data are organised to meet the requirements for further processing.

The memory space is used preferably for those parts of the data space where the data appear and, therefore, the method is more economical than a radar-sort-box organisation with a resolution capability of one search cell. The memory space necessary for the list processing technique grows linearily with the number of data to be stored as can be computed from the expressions given in the appendix.

For real time systems, it is very important, that even under the worst case conditions, the computing time of a process is bounded which is automatically fulfilled by the finite number of bits for the radar data, because binary subdivision is limited by that number. The computing time for updating or searching in the list grows logarithmically with the data number as shown in figure 6. The number of nodes to be searched is slightly undulating due to the fact that at certain abscissa values the data rather fill up subspaces than produce new subdivisions.

b.) P_F estimation

For P_F estimation, we search for that subspace where the estimation point lies in. Running through the search tree, we have converging environmental columina beginning with the root node representing the whole surveillance area. Because we have counted the data in each subspace, we can estimate the false alarm probability as the parameter of a binomial distribution. From this set of estimates, the false alarm probability for the search cell under consideration should be derived, for instance by weighted linear combination. But to specify the weights, some model for clutter distributions has to be assumed. To circumvent modelling, which seems problematic by the great variety of clutter distributions, only one subspace is chosen for estimation. The selected region has the property to be the largest subspace containing the probing point in which no data structure can be detected. Inside this region uniform distribution is assumed resulting in piecewise constant approximation of the three dimensional false alarm density function. Taking the estimation region as large as possible will reduce the variance of an estimator for binomial parameters by the greater number of search cells while smaller regions reducing bias are only formed, if there is more information by more data.

The largest subspace, in which no deviation from uniform distribution can be assumed is found by an hypothesis test on the data counts n_i in the subspaces. Under uniform distribution, these n_i are distributed as

$$P(n_1,n_2,\ldots,n_k) = \frac{n_0!}{n_k! \prod_{i=1}^{k} (n_{i-1}-n_i)!} \left(\prod_{i=1}^{k} \alpha^i\right)\cdot(1-\alpha)^{n_0-n_k}$$

where $\alpha=1/M$ represents the ratio of successive volumina. A test on uniformity is equivalent to a test on α, for which known methods like Chi-square or Maximum likelihood can be applied. We found that simple Tschebyscheff-Inequality discrimination works quite satisfactory because the error probabilities for a test on discrete count numbers can be stated only as inequalities.

IV. CONCLUSIONS

To summarize, the clutter map in the ELRA phased array system is a big data list in the central computer with subroutines for updating and searching. The TRIE list organisation preprocesses the data for subspace forming and estimation of P_F at any search cell in surveillance area can be done in less than one millisecond in a SIEMENS 7.748 computer. Real time updating during changing clutter is also possible and the described method acts as an adaptive three dimensional histogram. The discrimination between false alarms and target echos and further between false and true tracks is done on the basis of the estimated P_F value. Figure 7 and figure 8 show some simulated clutter data with one region of concentrated false alarms and the resulting subdivision of the surveillance area. Further studies for automatic detection of changing clutter distributions are planned after having analysed the stationarity of real clutter data in the ELRA phased array system.

APPENDIX

The memory space necessary for the TRIE list organisation technique and the computing time for updating or searching depend on the number K of nodes of the search tree. For $N_0>2$ uniform distributed data keys and subdivision in M equal subspaces, we get on the average (Knuth, 1973)

$$K_{N_0} = 1+M^{1-N_0} \cdot \sum_{N_1=2}^{N_0} \binom{N_0}{N_1} (M-1)^{N_0-N_1} \cdot K_{N_1}$$

where N_1 refers to the number of data in a subtree of the TRIE list organisation root node. This expression is not well suited for numerical analysis because of the binomial coefficients. Substituting corresponding expressions for further subtrees on the level i, i=1, ...h

$$K_{N_i} = 1+M^{1-N_i} \cdot \sum_{N_{i+1}=2}^{N_i} \binom{N_i}{N_{i+1}} (M-1)^{N_i-N_{i+1}} \cdot K_{N_{i+1}}$$

and setting $K_{N_h} = 1$ (data keys are all different and are represented by h-bit numbers), we get after multiplication and summation

$$K_{N_0} = 1 + \sum_{i=1}^{h} B_i \qquad \text{with}$$

$$B_i = M^i \cdot (1-(1-M^{-i}))^{N_0-1}(1+M^{-i}(N_0-1))).$$

B_i is the average number of all nodes on level i. In a similar way the processing time for searching a key can be obtained from the number of nodes to be visited

$$L_{N_0} = N+M^{1-N_0} \cdot \sum_{N_1=2}^{N_0} \binom{N_0}{N_1} (M-1)^{N_0-N_1} L_{N_1}$$

$$L_{N_0} = 1 + \sum_{i=1}^{h} C_i \qquad \text{with}$$

$$C_i = 1 - (1-M^{-i})^{N_0-1}.$$

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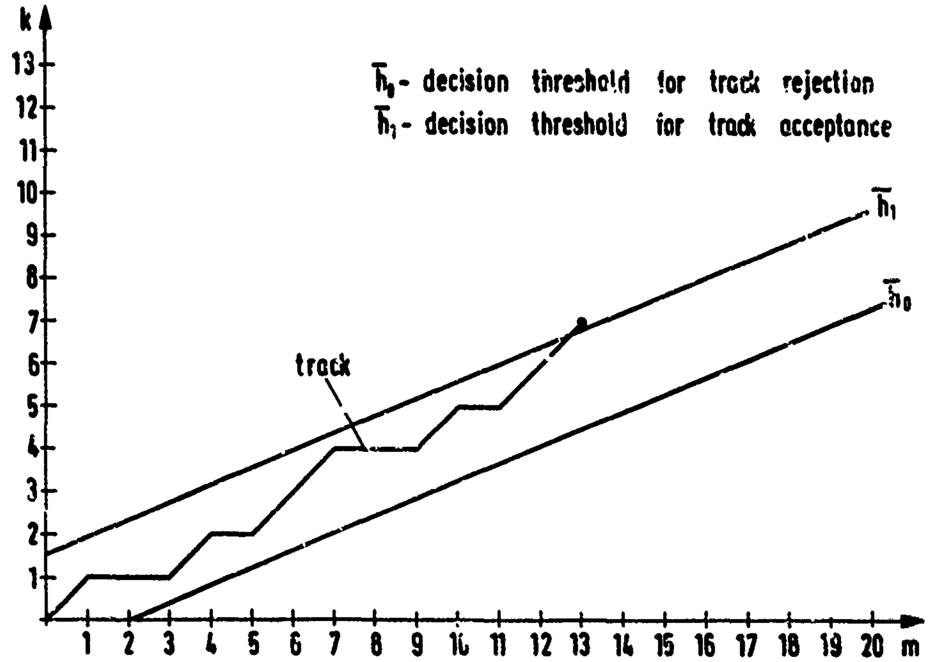

Fig. 1: (k, m) representation of a plot/no plot track development

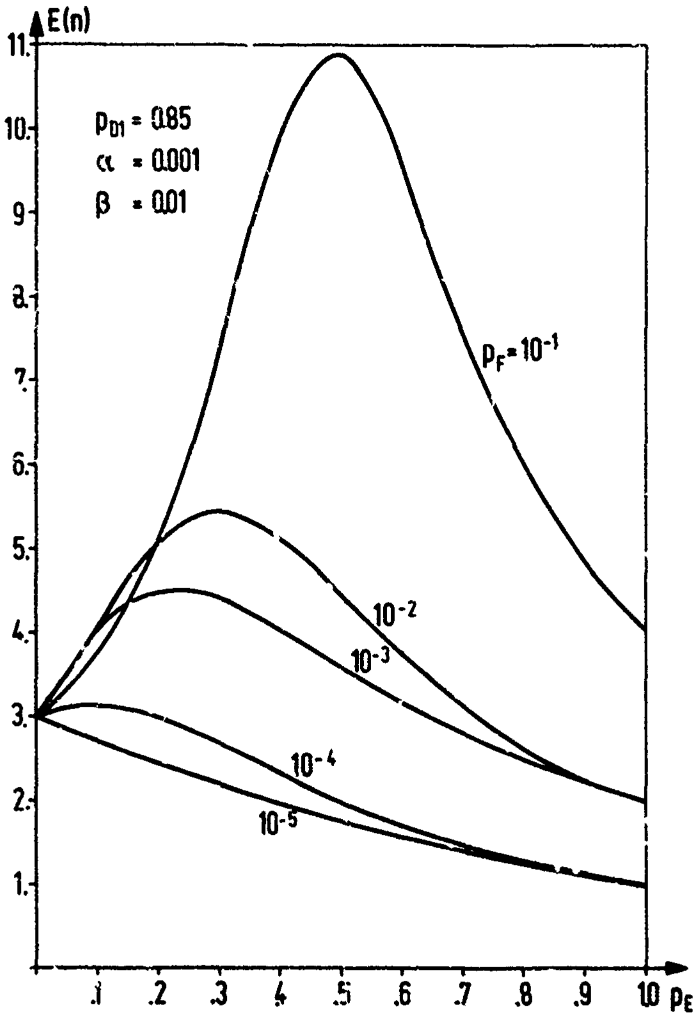

Fig. 2: Sequential track initiation, average test length

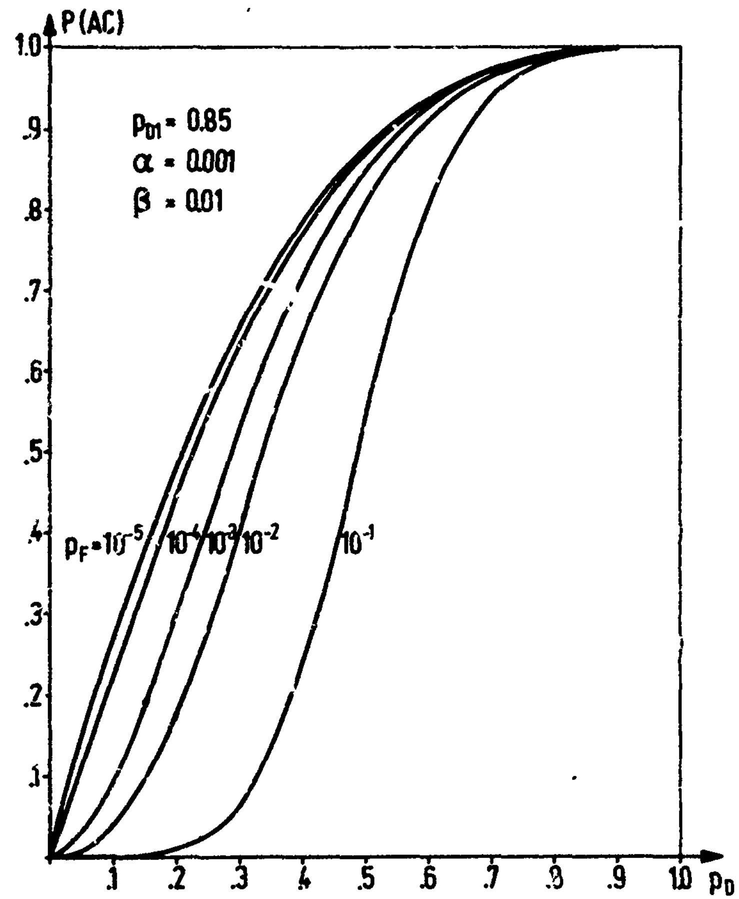

Fig. 3: Track acceptance probability

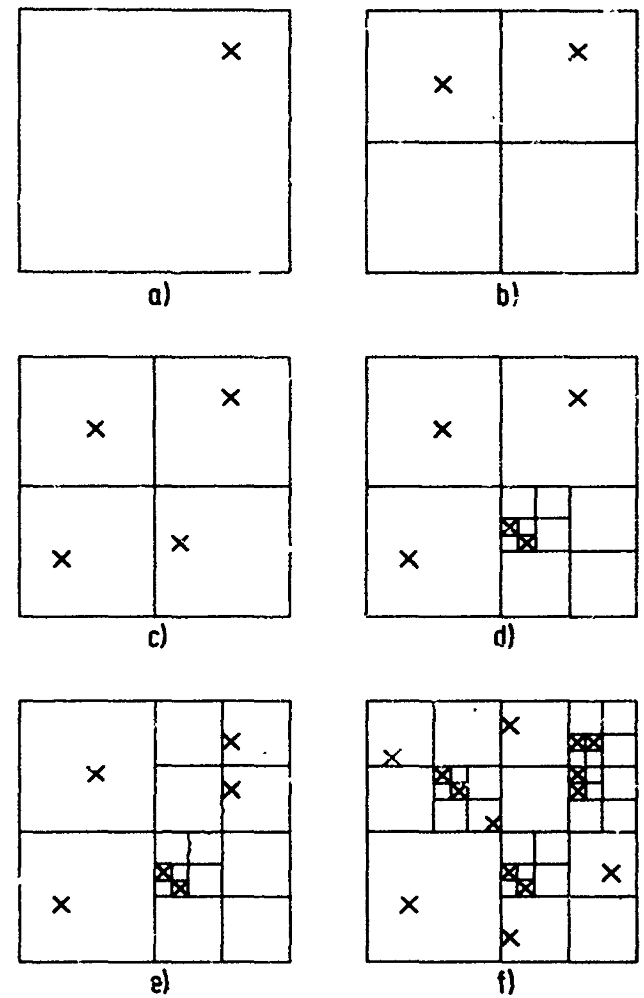

Fig. 4: Successive divisioning of the data key space by the TRIE list organisation technique

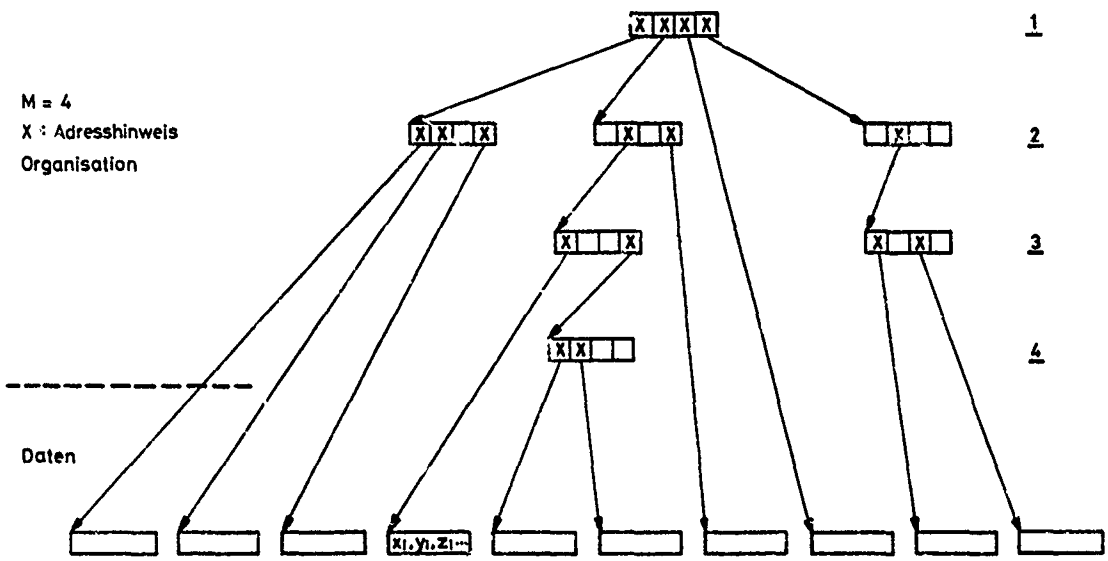

Fig. 5: Search tree for TRIE list organisation technique

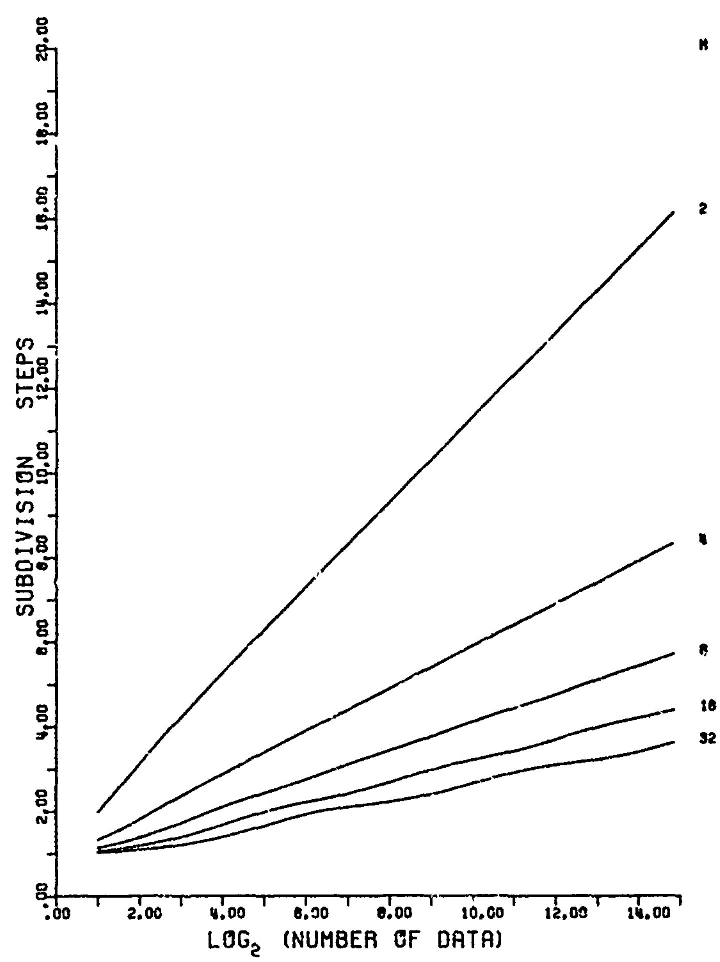

Fig. 6: Number of nodes to be searched for data retrieval

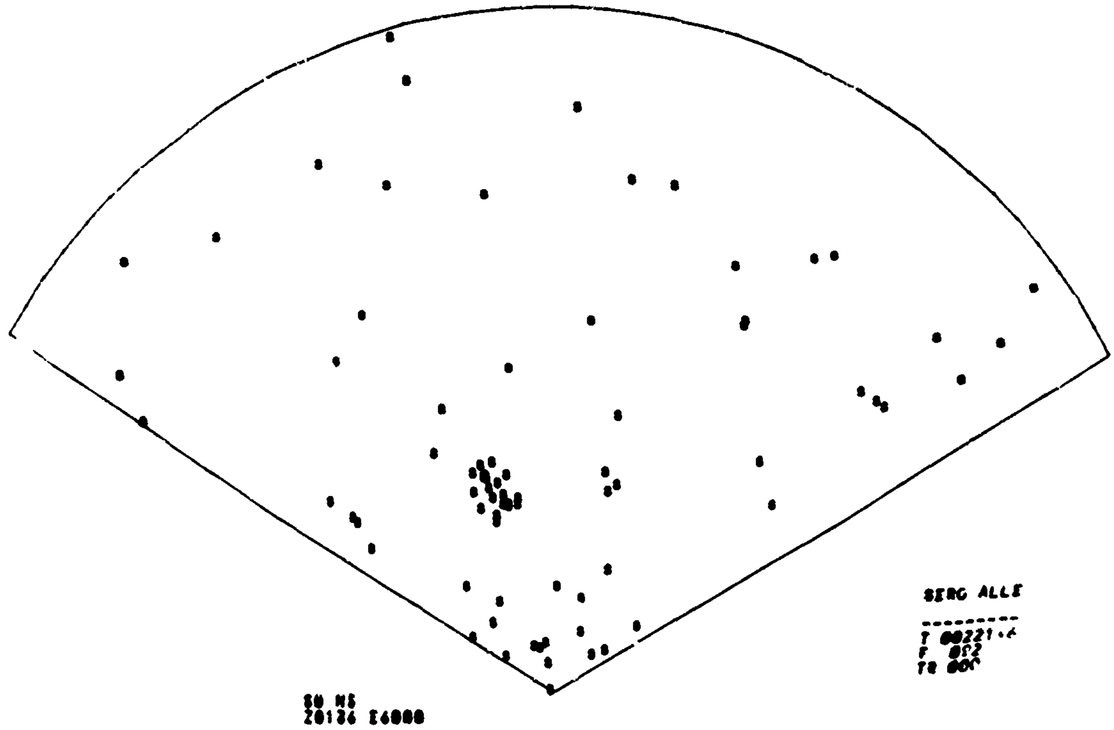

Fig. 7: Simulated false alarms in the ELRA surveillance area

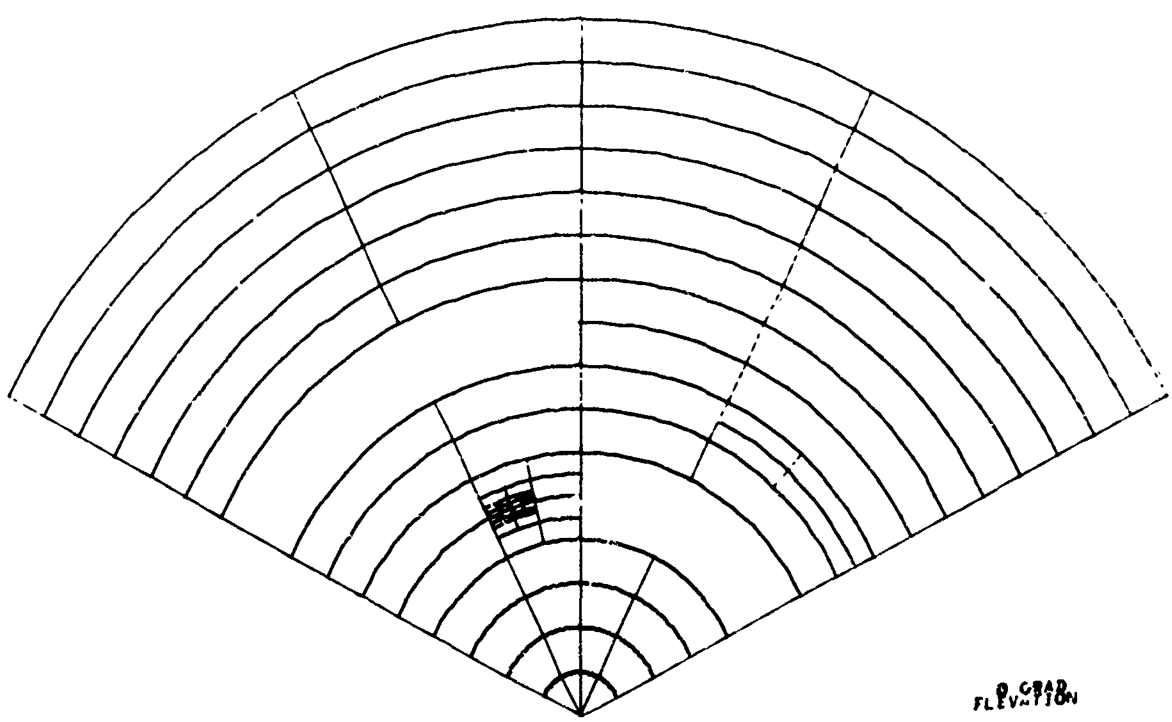

Fig. 8: Resulting subdivision from the clutter data of Fig. 7
at the elevation 0 degree

DISCUSSION

H.B.Driessen, Netherlands

Can you please indicate what the accuracy is of your estimate of the false alarm rate?

Author's Reply

The accuracy depends on the number of data collected. In our ELRA system we can store, due to core memory restrictions, about 2000 data sets, which result in an estimator variance for the parameter of several percent.

H.B.Driessen, Netherlands

For your sequential detection procedure, an estimate of both P_F and P_D is needed. How are they obtained?

Author's Reply

P_D is not estimated, it is a fixed parameter of the detection unit. Remember that P_D is defined as the minimum detection probability. It can always be achieved with a phased array radar by integrating enough pulses.

Software Structure and Sampling Strategy for Automatic Target Tracking with a Phased Array Radar

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SUMMARY

Starting with a brief description of the software system used for multi-target tracking in the experimental phased array system under construction at the FFM the paper introduces into the application of Kalman Filters for tracking maneuvering targets. In contrast to the situation with conventional radars the additional degree of freedom to adapt the scan period on the estimated lack of information with regard to each individual track is analysed for the electronically steerable radar case. A sampling strategy is developed and analysed that minimizes the tracking frequency considering the shape of the detection probability within a tracking beam pointing towards the predicted target position. Adapting the scan interval a constant track accuracy in space can be achieved taking the various dynamical and geometrical restrictions into consideration. An optimal spatial extension of this uncertainty volume can then be derived. As the sampling frequency of course also depends on the assumed maneuvering capabilities of the target under track, the extension of the optimal uncertainty volume depends only on the beam splitting ratio of the used monopulse angle finding technique.

1. INTRODUCTION

Phased arrays are moving from the laboratory to development and tests, but the multi-faceted area of signal processing, automatic multi-target tracking and system control contains a variety of problems, which generally have not been solved. The trend towards unconventional radars has been forced by increasing operational necessities and follows from the enormous progress in digital and analog components in the last decade and from the progress and availability of fast computers.

The electronically steered radar (ELRA) project (Wirth, W.D., 1977) conducted at the FFM institute in Werthhoven (FRG) serves as an experimental system to identify and analyse important problems of phased array technology. The ELRA system itself is not designed for any particular operational use, so our work is mainly research oriented.

We artificially split the whole phased array project into two - to some extent different - areas: the radar oriented signal processing part and the processing and control of the radar data in the central computer. The interface between both the fields of research can be seen in the process computer (Hanle, E., 1978).

Our system configuration is demonstrated in fig. 1. From the antenna down to the central computer and display system we observe a data reduction, or reduction in bandwidth of about $1:10^5$. The structure of the digital data fed into the central computer is of no further interest here, but it should be explained what sort of information transfer in both directions has been provided. Basing on the stored knowledge and a priori information in the central computer a limited set of search cells can be created and transferred to the process computer to concentrate on in the search mode of the phased array. When the search routine has processed these cells, the central computer generally sends a different set to continue the process after having received a particular "end message". Results from this search mode are digitized "echoes" containing time, distance, doppler, angles and signal strength information. The search command organisation should not be detailed further.

In addition the central computer can generate track commands generally specifying only one beam direction, range and doppler gate and expected signal strength of an object to be detected and tracked. The track commands and the search activity are merged at the stage of the process computer (Hanle, E., 1978). As a result of a track command a record is formed containing the above specified information and is transferred into the central computer with a time delay not longer than some 50 ms. Sometimes a special message of course is necessary to state that no target could be found in the characterized area.

As can be seen from fig. 1 the system can be operated in a real-time real-data mode of operation and also under real-time conditions by simulated data and control facilities. We simply have to load an appropriate simulator program into the process computer without changing the real-time program of the central computer or the interfaces. The simulator then replaces the process computer program normally used for experiments. This technique has been of great importance, during the phase of software production for test and detailed analysis under reproducible conditions (Baltes, R. et al., 1977).

2. SOFTWARE DESIGN FOR MULTIPLE TARGET TRACKING

In contrast to a conventional rotating radar the full flexibility of the phased array system should extend to the central computer's software. This of course can only be achieved approximately. However the well known structure of automatic tracking programs in use for conventional systems cannot be applied here. This mainly depends on the provided feedback from the central computer to the radar system to make use of the beam agility. In our system the individual radar data gathered in specific data pools of the central computer do not start any kind of processing by their appearance but a scheduler controls the various processes basing on the condition and resources of the whole system. In addition the tracking program should not work in the so called track while scan mode but in a computer controlled one. Each track initiation process and each established track is considered as an individual process conducted by the scheduler. The following modules of computer activities referring to an individual track have been provided (list is not complete):

A) predict the present target position (state)
B) send a track command
C) check whether data referring to the track have been received
D) correlate the data with the track
E) decide on further track commands if data have been identified to be insufficient
F) do the data filtering
C) calculate the time gate for the next track command

The logical ordering from A to G is obvious. These activities conducted by the scheduler form individual chaines or processes referring to each track initiation or tracking process. Basing on the estimated lack of information for each individual track (stored in the general track file) individual track commands are generated according to a scanning strategy that will be detailed later on. Therefore the elements of the stream of track commands sent to the radar generally belong to different targets under track and track initiation processes. In overload situations processes of higher priority (belonging to targets of higher interest) may delay track commands and filtering jobs of lower priority tracks a little, without unacceptable degradation of the whole system. Such an organisation has of course very good recovery properties if we are mainly thinking of short bursts of computer or radar overload. No artificial measure of load needs to be introduced in order to control the stream of processes. In cases, however, of severe overload lasting over a longer period of time, some tracks of lower interest or initiation processes in areas of lower improtance will be cancelled automatically when the estimated probability of a successful engagement is too small. By this means the maximum tracking range and activities in particular fields of minor interest can automatically be reduced by an appropriate priority scheme to distinguish and order the various phased array processes.

This organisation meets the requirement of computer controlled multi-target tracking very well. The interference between search, track initiation and tracking functions can easily be handled. The main advantages provided are:

- The main functions of track initiation and tracking are decoupled (as fully as possible).

- The scan time (data innovation interval) for all targets under track can be adapted individually to the estimated lack of information or to meet operational requirements.

- By pointing the track command as exact as possible towards the target direction the S/N ratio can be increased. Simultaneously the localization error in both angles can be reduced.

- The well known blow up of correlation gates of targets tracked while scan during phases of lower detection probability can drastically be reduced by increasing the sampling frequency adaptively.

- In computer controlled tracking it is of interest to predict the doppler shift and the number of targets within the considered range gate to improve the detection mechanism.

- Each target can be tracked under its individual priority. Graceful degradation under overload conditions can be programmed easily.

We learned that the whole program system should be written in higher language except for a limited number of special routines which had to be written in assembler language after we identified that they in fact are critical. Except for the I/O-organisation no further interlacing with the operating system of the computer has been found to be necessary.

3. TRACKING ALGORITHMS

Tracking algorithms for state estimation, prediction and data correlation are the backbone of each automatic tracking program although they normally do not consume the overwhelming fraction of computer time. As can be seen from literature the today's trend leads to a more or less complex Kalman Filter to solve the above mentioned problems in a comprehensive way. For high accuracy tracking and to incorporate doppler information (measured radial velocity) a stage three (position, speed, acceleration), fully coupled Kalman Filter seems to be very well suited. This especially is true for small data intervals. By carefully writing the mathematics in reasonable form and avoiding unnecessary operations in the produced program code the computer load of the whole processing cycle (not containing the plot to track correlation part) comes out to be about 5 ms/track for a today's high speed machine. Depending on V^2/r (target distance r, target velocity V) the coupling of the three dimensional space coordinates is not necessary. This decoupling saves a factor of about 4 of computer load; mainly because the covariance matrices are smaller and geometry is easier.

Nevertheless the underlying assumptions of the target dynamics are too general and simple for many applications. Normally the acceleration process of the target under track is modelled as a Gauss-Markoff process with vanishing mean and variance Σ (m/sec^2). In addition a correlation time Θ (sec) can be introduced to describe the rate of change of target maneuvers in the course of time. By selecting appropriate model parameters a reasonable behaviour of the track will be found in many cases but there remain significant discrepancies for target plants that are not similar to the Gauss-Markoff type. Simple but important examples are straight line flights interrupted by short changes of target heading. In those cases adaptive processing algorithms are used. This point will be regarded in chapter 5.

The tracking algorithm has to be considered in context with a tracking strategy. For instance the measures against unwanted false tracks created by false alarms or man made corruptions of any kind are part of the tracking strategy. This question is of importance for track initiation in a cluttered environment (Fleskes, W., 1978) under dense target situation (Binias, G., 1978), and also for conducting an established track of a single target through a cluttered portion of space. In contrast to the situation in multiple target environments we have identified that for a single target case the well known technique of nearest neighbour plot to track correlation or any procedure of averaging many returns in the target's correlation gate leads to shorter true track lengths than the following method: All situations of correlation conflicts (more than one correlating echoe) should be bridged by neglecting all returns and proceeding as having received no return at all. In those situations a new track command is generated with only a short time delay. This method should be continued until we receive one and only one return correlating to the track. In addition the set of not processed echoes is used to estimate the false alarm probability P_F in the environment of the track. Basing on this we can decide whether tracking is possible or not. This of course can lead to a cancellation of tracks in severe clutter if P_F is estimated to be so high that the tracking process would become unstable and the estimated success of tracking would be too small. In those cases no resources should be wasted and the track should be terminated.

Fig. 2 demonstrates theoretical results from one-dimensional simulations verified by simulations. The probability of track distortion during a 20 sec period of track is demonstrated depending on the false alarm probability P_F. P_F has been normalized to the variance of position noise. There strategy 1 refers to arithmetic mean of all received returns while 3 refers to the above mentioned repetition strategy. The nearest neighbour strategy has turned out to be worse than 1. As parameter the tracking interval in seconds is given. We further conclude from these results that the tracking mechanisms can to a great extent be stabilized by increasing the tracking frequency. This of course is only necessary in areas of pronounced distortion which should be known before the track enters into. Further techniques to automatically detect and cancel false tracks should not be detailed here (van Keuk, G., 1977).

4. A SAMPLING STRATEGY

In this chapter some arithmetics can not be avoided. Let $Z(N)$ denote the state vector of a target under track at an instant of time labelled by N. For the sake of simplicity we assume a one dimensional target state

$$Z'(N) = (x(N),\ \dot{x}(N),\ \ddot{x}(N)).$$

We assume the following plant model of the target motion

$$\ddot{x}(N+1) = E\cdot\ddot{x}(N)+\Sigma\sqrt{1-E^2}\cdot u(N)$$

$$Z(N+1) = \begin{pmatrix} 1 & T & \frac{1}{2}T^2 \\ 0 & 1 & T \\ 0 & 0 & E \end{pmatrix} Z(N)+w(N); \qquad E = e^{-T/\Theta}$$

$$w(N) = \Sigma(1-E^2)^{\frac{1}{2}}\begin{pmatrix} 0 \\ 0 \\ u(N) \end{pmatrix}.$$

$Z(N)$ models a target motion driven by a Gauss-Markoff process of acceleration. Hence $u(N)$ is a sequence of uncorrelated (0,1)-normal distributed random variables.

The measuring equation connecting the state and the measurement Y has the form

$$Y(N) = Z(N)+s(N).$$

In the error covariance matrix $S(N)$ of s we have to consider that only a part of the state generally can be measured. The rest of the not measured quantities is represented in S by infinite numbers. This scheme is very well suited for the application of a Kalman Filter. This should not be explained here down into details. The Kalman Filter produces conditional estimates $\hat{Z}(N|N)$ for the state at a time labelled by N (after processing of all available data up to N) and gives also the related error covariance matrix $V(N|N)$ in a recursive way. Starting from the filtered state this can also be propagated to obtain a predicted state related to a covariance matrix P accordingly. The whole processing algorithm forms a linear filter in the state space of the target. The set of parameters normally includes:

σ : variance of position noise at the target position
Σ : variance of the target acceleration
Θ : correlation time of maneuvers
T : scan interval (data innovation interval).

All these quantities may (and generally will) change during target flight. The error covariance matrix P tells us the uncertainty of the predicted state of the target under track. Especially the 11-element refers to the look ahead position accuracy. If the above quoted parameters are constant (finite and not vanishing) the sequence $P(N+1|N)$ converges as N increases to the so called local stationary tracking covariance. For application these limiting values are not of interest because the target moves in space and therefore the tracking is not stationary. But the limits are of interest for any theoretical investigation. No closed expression for these quantities are available, but we found an appealing approximative formula of the following form ($P := P_{11}(N+1|N)/\sigma^2$)

$$T = 0.4\left(\frac{\sigma\sqrt{\Theta}}{\Sigma}\right)^{0.4}\cdot\frac{P^{1.2}}{1+\frac{1}{2}P}$$

which is valid for σ(10-500 m), Σ(2.5-30 m/sec^2), Θ>20 sec, T(0.1-5 sec) within an accuracy of about 5 %.

Now the question is: how should we select the data interval T. If we select too large an interval we are risking the loss of track, because the area to predict a track naturally increases with growing T. If on the other hand we use too small a T the track may be oversampled in some sense. We introduce the following sampling strategy:

$$\text{Find } T_{N+1} \text{ from } P_{11}(N+1|N) = \sigma^2 V_0^2.$$

This reads in simple words that the target normally will be tracked when the look ahead prediction accuracy $P_{11}^{\frac{1}{2}}$ crosses $V_0\cdot\sigma$. Hence $V_0\cdot\sigma$ is the tracking uncertainty in space. V_0 is a scalar quantity relating the uncertainty to the local position noise variance σ. If V_0 is taken to be much smaller than 1 there sometimes may not exist a solution of the above equation. In those cases select the lowest possible data innovation interval. For

constant parameters ($\sigma, \Sigma, \Theta, V$ finite and non vanishing) the sequence T_N converges to the stationary tracking interval T. Again these stationary quantities are more or less only of theoretical interest to analyse the sampling strategy. In practice the scan intervals have to be calculated from the above equation.

From our approximative formula we have

$$T = 0.4 \left(\frac{\sigma\sqrt{\Theta}}{\Sigma}\right)^{0.4} \cdot \frac{V_0^{2.4}}{1+\frac{1}{2}V_0^2} .$$

Understanding $P_{11}(N+1|N)$ as a measure of the lack of information concerning the track, we can say that by applying our strategy we simply adapt the scan period T to the present estimated lack of information. This leads to a constant track accuracy in space. Especially in the phase of track initiation when there is a pronounced lack of information regarding speed and acceleration this automatically leads to an increasing sampling frequency settling in the course of time to T^{-1} depending on the increasing knowledge stored in the filter. This can be seen from fig. 5.

The question remains how to fix the parameter V_0 describing the spatial extension of the target's predicted position, if V_0 is not defined by additional operational requirements.

If we do not point our track command towards the true target position we are risking a reduction of detection probability. Let us assume

$$P_D(x) = P_{DO} \cdot f(\vec{x}^2/B^2)$$

for instance

$$P_D(x) = P_{DO} \cdot e^{-2\vec{x}^2/B^2}$$

with the deviation $\vec{x}$ between the true and the predicted target position and B relating to the width of the tracking pencil-beam. While we observe the detection probability P_{DO} by pointing towards the target ($\vec{x}=0$) we are modelling the reduction of P_D by incorrect pointing ($\vec{x}\neq 0$). If we could not detect the target we of course have to iterate our track command immediately following our sampling strategy. This is a source of additional load for the whole system. The mean number of iterations necessary to find the target can simply be calculated from

$$E[n] = E\left[\frac{1}{P_D(x)}\right]$$

$$= \frac{1}{P_{DO}} \left(\frac{1}{\sigma V_0 \sqrt{2\pi}}\right)^2 \cdot \int dx_1 dx_2 \, e^{-\frac{x_1^2+x_2^2}{2\sigma^2 V_0^2}} / f(\vec{x}^2/B^2)$$

$$= g(V_0^2\sigma^2/B^2)/P_{DO}$$

for a two dimensional example where x_1, x_2 mean both the angles of the tracking device.

For the special case of our example we have

$$E[n] = \frac{1}{P_{DO}} (1-4V_0^2\frac{\sigma^2}{B^2})^{-1} \quad \text{for } V_0 < \frac{B}{2\sigma} .$$

Calculating the overall load the data innovation interval T between two successful target localizations has also to be considered, leading to the following mean load L

$$L = \frac{E[n]}{T} .$$

Making use of the structure of the approximative formula for the stationary scan interval T:

$$T = a(\frac{\sigma\sqrt{\Theta}}{\Sigma}) \cdot b(V_0)$$

we have

$$\lambda = \frac{J(V_0^2 \frac{\sigma^2}{B^2})}{P_{DO} a(\frac{\sigma\sqrt{\Theta}}{\Sigma}) \cdot b(V_0)} .$$

It is of course reasonable to minimize the mean load by looking for an optimal parameter V_0. It can easily be seen that this optimal V_0 parameter does not depend on $P_{DO}, \Sigma, \sigma, \Theta$ but only on the "beam-splitting ratio" σ/B. Here σ/B depends on the used monopulse device and of course on S/N too. To find V_0 for our example we have to minimize

$$(1-4V_0^2 \frac{\sigma^2}{B^2})^{-1} \frac{1+\frac{1}{2}V_0^2}{V_0^{2.4}} \rightarrow \text{Min.}$$

Having fixed $V_0 = V_0^{opt}(\sigma/B)$ we of course can calculate the corresponding scan interval from our formula. T then depends on the rest of parameters in form of $(\sigma\sqrt{\Theta}/\Sigma)^{0.4}$ as stated above.

Fig. 4 shows the optimal parameter V_0 depending on the beam splitting ratio σ/B.

As has been mentioned the scan period T not only depends on the relative tracking accuracy V_0 but also on the cinematical parameters Σ, Θ of the target model and the local position noise variance σ. We generally have a dependence of σ of the form (target distance r)

$$\sigma = r \cdot f(S/N).$$

In our ELRA system σ will be derived from the estimated S/N ratio of the individual target under track. The exact form of σ will be very complex, hence fig. 5 shows two curves of possible $\frac{\sigma}{B}$ values. The corresponding typical scan periods referring to an optimal chosen V_0 and cinematical parameters Σ=20 m/sec²; Θ=30 sec are shown in fig. 6.

From our formula for T we can also see how the knowledge about the maneuvering capability of the target under track will influence the local stationary scan period (system load). To detail this let us compare two types of aircraft A, a highly (Σ=30 m/sec²; Θ=20 sec) and B a modest maneuvering one (Σ=5 m/sec²; Θ=300 sec). Then we find from our formula a quotient of the related stationary scan periods T_B/T_A of about 3.5.

5. ADAPTIVE TARGET TRACKING

The above explained adaptation of the scan period T on the estimated lack of information has not disturbed the linearity of the tracking filter. This mainly depends on linearity again considering that the error covariance matrix P does not depend on the echoes processed. Therefore the tuned scan interval does not depend on the data and the filter algorithm remains to be linear. In practice there is of course a very small dependence because the target position enters through the position noise variance. But this nonlinear effect is in fact very small and can be neglected in the sense of an extended Kalman filter.

If we try to estimate the cinematical target parameters Σ, Θ during track to identify different phases of motion of the target, then we have to calculate them from the data processed and the whole processing scheme becomes nonlinear. Nevertheless the scanning strategy introduced in chapter 4 remains valid. By adaptation of Σ, Θ two different phenomena will occur. We obtain better filtering performance in phases of more correlated target motion and in addition the scanning frequency will be reduced applying our scanning strategy. The theoretical limit of saving of radar and computer resources by adapting T can be calculated assuming an ideal nonlinear tracking device that without any error nor time delay adapts our cinematical parameters to the present target state. The example of chapter 4. for instance showed a saving of about 3.5.

In practice this factor cannot be achieved because the ideal feedback device to tune Σ, Θ is not realizable and moreover our model of the target dynamics is not correct. The crux is that the different phases of target motion can suddenly change. Hence we need a sensitive and therefore noisy feedback organisation to control the filter parameters during track. So we only shall have pronounced differences in the adapted scan interval if we select very different models of target dynamics as has been explained above. In addition we need a very sensitive filter design.

Facing this we decided to have two parallel filters for target tracking one of which assumes a straight line unaccelerated target plant while the other one assumes worst case target maneuvers all over the time. A special test setup observing the innovation processes decides whether the one or the other filter is correct. This leads to a very robust concept of adaptive filtering that meets the above mentioned requirements very well. Moreover the beam agility of the phased array can be used to overcome critical phases of uncertain target motion by temporarily increasing the sampling frequency. This has been realized by making use of a sequential mismatch detection device that automatically calls for additional data in phases when no hypotheses can be accepted. Here we should emphasize that in cases of precisely measured doppler information the sensitivity of the mismatch detection device can be increased considerably by simply looking into the $\dot{r}$ innovation process too. This should not be detailed here because it has been published (van Keuk, G., 1975).

Fig. 7 demonstrates a typical example of a maneuvering target under track. You can see the TURN and NOTURN detection points, the varying accuracy of heading estimates reflecting the filter-performance and the adaptively controlled scan intervals during flight.

Fig. 8,9 demonstrate recent experimental results from our ELRA system. In fig. 8 you can see a section of a low level (500 m above ELRA, 50 m/sec speed, about 1.5 sec scan interval) track crossing the Rhine river at a distance of about 15 km from the ELRA site. Fig. 9 gives a detail of the track showing the estimated target positions (+) and the speed vectors. The histograms of plot-to-track differences and estimated track detection probability correspond to the demonstrated section of the track. The symmetry of the histograms (especially that for the azimuth u) confirms a satisfying behaviour of the tracking device and a good tracking accuracy. False alarms in the environment of the true track have automatically been removed by the false track suppression capability of the program system.

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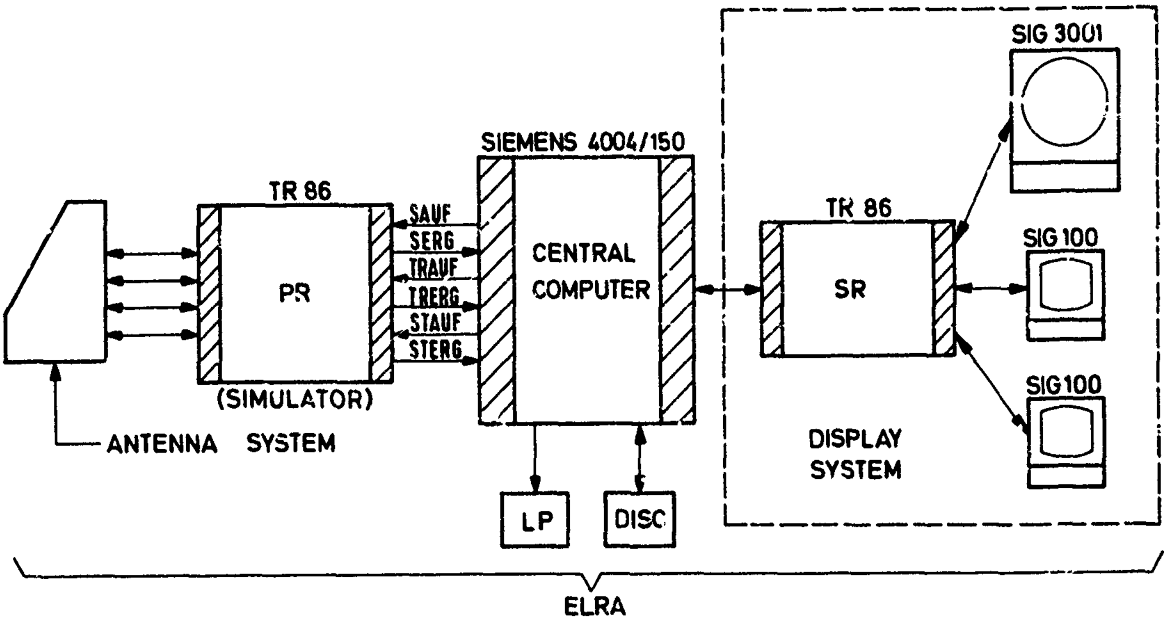

Fig. 1: ELRA system configuration

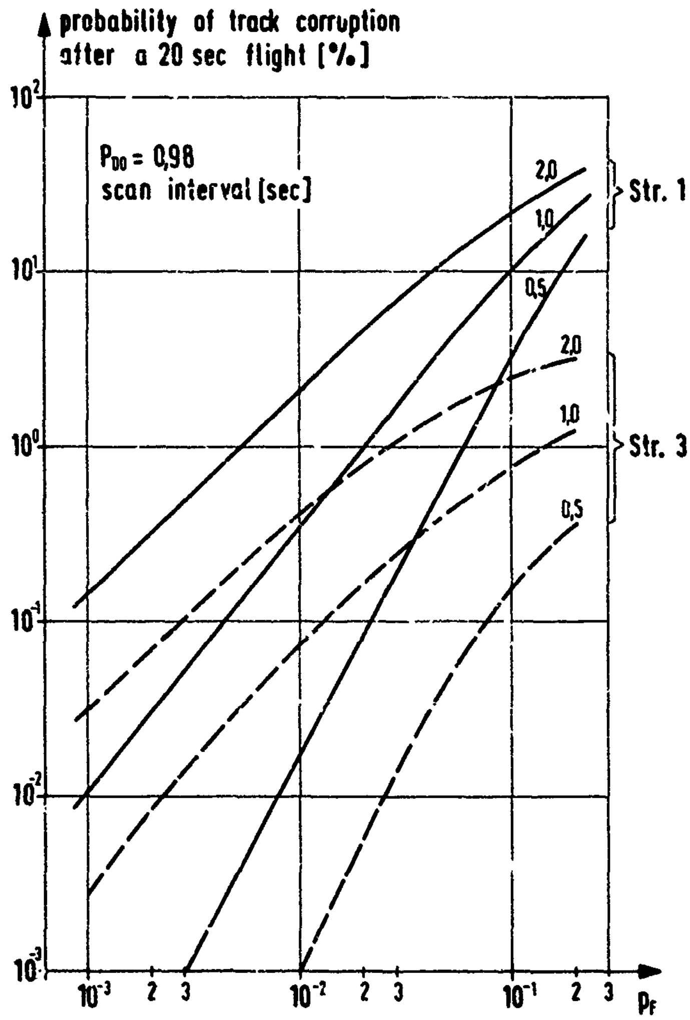

Fig. 2: Probability of track distortion
(one-dimensional tracking, P_F normalized to the variance of position noise)

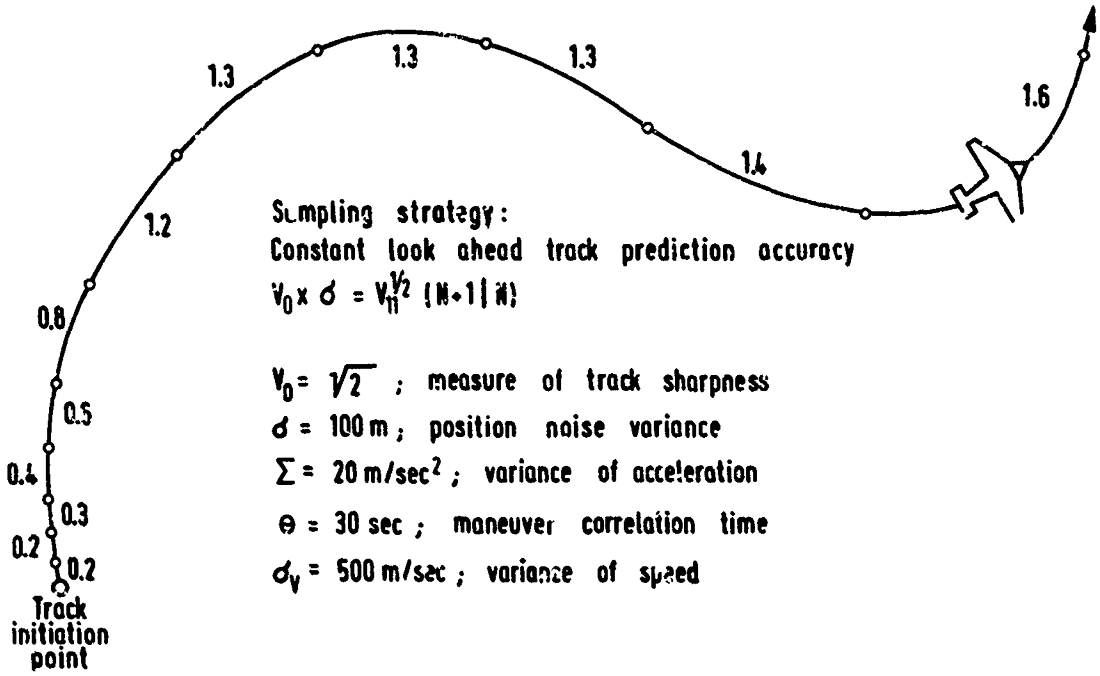

Fig. 3: Track initiation

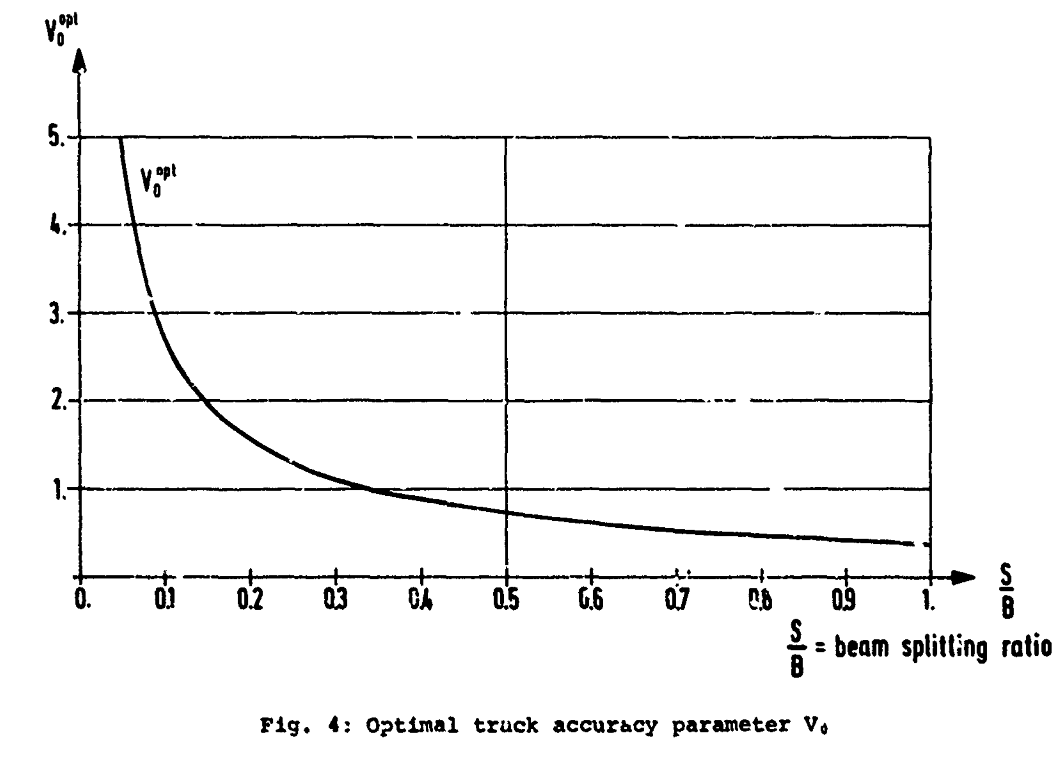

Fig. 4: Optimal truck accuracy parameter V_0

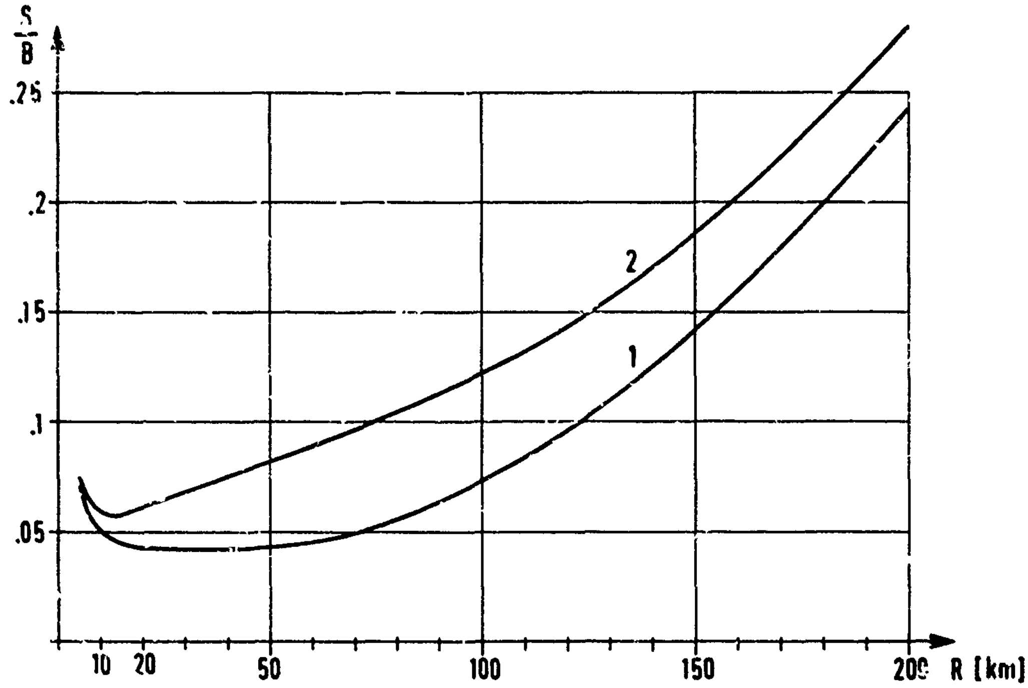

Fig. 5: Beam splitting ratios

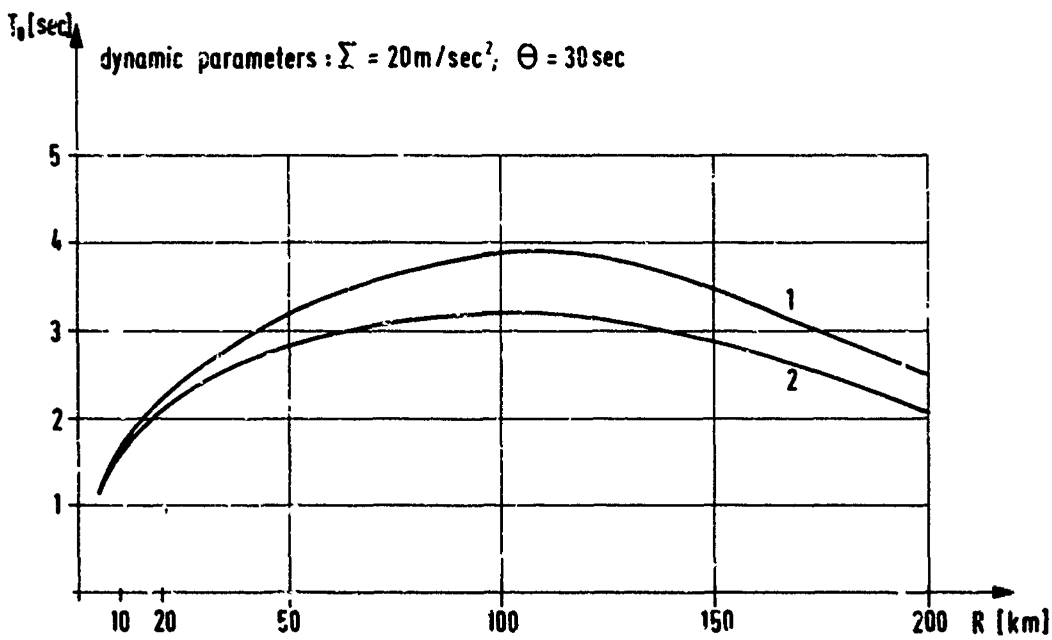

Fig. 6: Scan intervals

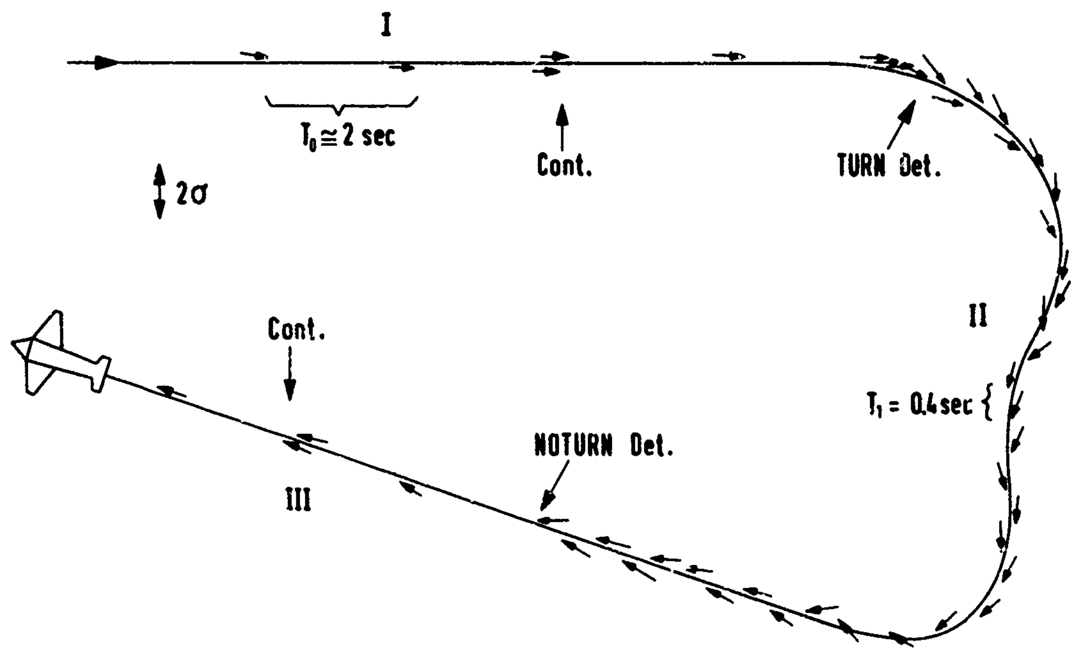

Fig. 7: Adaptive target tracking output

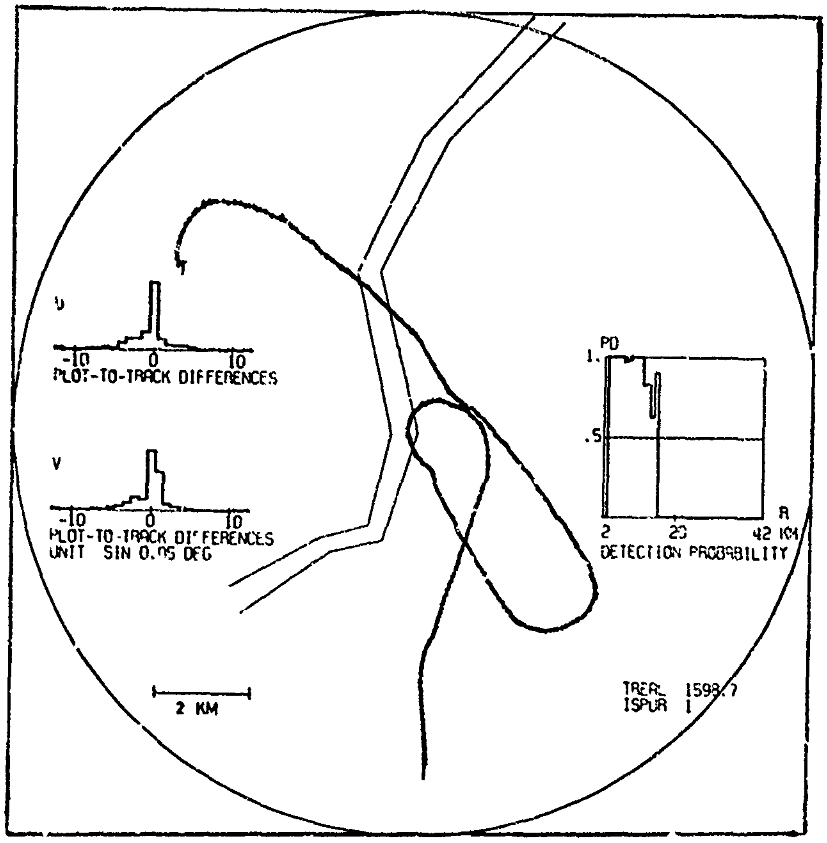

Fig. 8: Experimental results from ELRA

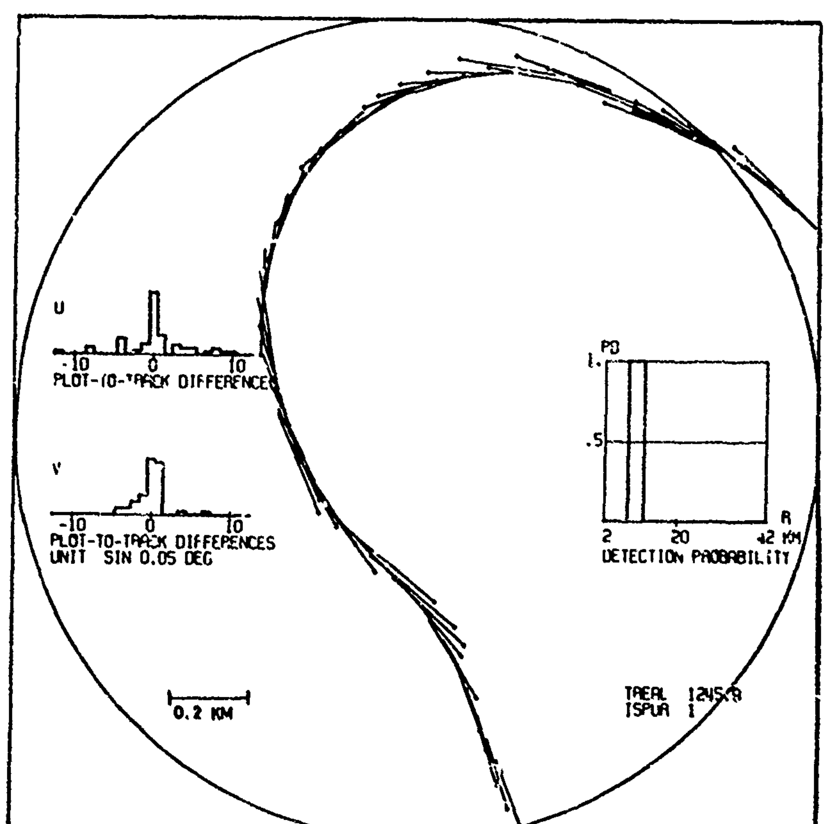

Fig. 9: Amplified part of Fig. 8

DISCUSSION

S.J.Rabinowitz, USA

What is the reduction in radar power which results from the use of an adaptive versus a fixed tracking strategy?

Author's Reply

The scan interval per target varies from about 0.1 seconds to about 5.0 seconds. In track initiation we need a higher tracking frequency that in track maintenance. Therefore, the system load per target varies by one order of magnitude and there is a considerable saving by using an adaptive sampling strategy.

The Formation Tracking Procedure for Tracking in Dense Target Environment

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SUMMARY

The basic principle of automatic target tracking is plot-to-track correlation. In case of dense target environment plot-to-track correlation is often disturbed by incorrect plots which cause a correlation-conflict. Well-known measures against the correlation-conflict are the Nearest-Neighbour-Rule and Branching-Procedures. But there are airspace situations, e.g. target formations, where these measures fail to solve the conflict or necessitate great demands of computer-time and computer-storage.

We, therefore, developed an alternative strategy of tracking in dense target environment. The strategy of Formation Tracking is characterized by the substitution of raid tracks for single target tracks. The raid tracks are correlated and updated by plot-clusters. The formation track consists of one central track and several marginal tracks containing the whole information about the mean cinematical behaviour and the spatial extension of the tracked formation.

Special investigations were directed to the following problems: Formation track initiation, formation track evolution, decision- and control-procedures with regard to formation track splitting, and formation track junction.

The efficiency of formation tracking will be demonstrated by a few one-dimensional examples of appropriate airspace situations.

INTRODUCTION

The principal steps of computer controlled single target tracking in connection with a phased array antenna are

- state prediction of the tracked target,
- scanning of the expectation volume,
- plot-to-track correlation,
- processing of correlating plots.

Under real environment conditions plot-to-track correlation is often disturbed by false plots (clutter, noise) and incorrect plots originating from targets which are in close proximity of the target under track (formation).

Because of different aims in dealing with single target tracking in dense clutter environment and the tracking of formation targets (tracking in dense target environment) we carried out distinct investigations of these two problems (van Keuk, G., 1977; Binias, G., 1977); and, in opposition to some other authors (e.g. Jaffer, A.G., et al., 1972; Singer, R.A., et al., 1973), we developed different methods to solve these two problems.

According to this distinction the "dense target"-situation is described by

> a group of closely spaced single targets (distances about 100 m or less), which move on nearly parallel target trajectories (i.e. parallel with small random disturbances).

This situation is of significant importance especially in the military application of target tracking. Formation flights are nowadays normal military aircraft operations

(e.g. for attacks on distributed target areas and for penetration). Beyond that, the "dense target"-situation occurs in the observation of multiple weapon systems (e.g. aircraft-missile systems and multiple missile systems).

PROBLEMS OF SINGLE TARGET TRACKING IN DENSE TARGET ENVIRONMENT

Figure 1 demonstrates the correlation conflict. This conflict arises in computer controlled single target tracking as soon as neighbouring members of the formation produce track plots T which appear in the intersection of the two expectation gates. Then the automatic tracking procedure will have to decide which track plot T should be associated with the appropriate search plot S (track initiation). The probability of this correlation-conflict is a function of target distance d and scanning time interval T. We assumed decoupled tracking in cartesian coordinates and calculated the minimum target distances d_{min}, which are necessary in case of track initiation in order to push the conflict probability below a certain limit of $P_c \leq 0.001$. In Figure 2 these minimum target distances d_{min} can be compared with one half of the one-dimensional extension of the expectation gate DIFA.

The various measures proposed to avoid the correlation conflict can be reduced to two substantial principles:

Application of the Nearest-Neighbour-Rule,
Application of Branching Procedures.

The Nearest-Neighbour-Rule (Jaffer, A.G., et al., 1972; Singer, R.A., et al., 1973) prescribes correlation of the track plot, which is nearest to the center of the expectation gate. In case of dense target environment this rule may produce miscorrelations, i.e. association of search- and track plots originating from different targets. Miscorrelations generally produce deviations of track and target trajectory which finally lead to target loss. We assumed three targets on parallel trajectories and calculated the minimum target distances d_{min} which are necessary to keep the miscorrelation-probability during track initiation below $P_{mc} \leq 0.001$. Figure 3 shows that these minimum target distances d_{min} exceed the assumed target distances within formations (ca. 100 m) by a factor of 3.5 even in case of very small scanning time intervals.

A detailed description of Branching Procedures (Singer, R.A., et al., 1974; Smith, P., et al., 1975) developed to handle the correlation-conflict goes beyond the scope of this presentation. Branching, however, is generally characterized by an unavoidable increase of the number of branch-tracks in comparison to the number of real targets. Branching, therefore, demands increased expense with regard to processing time and computer storage.

GENERAL DESCRIPTION OF THE FORMATION TRACKING PROCEDURE

The various attempts of solving the correlation conflict in dense target environment by means of single target tracking generally fail in working with small target distances. We, therefore, looked for an alternative strategy substituting single target tracking in case of dense target environment. We approached this strategy by an examination of the requirements which have to be fulfilled by a computer controlled tracking procedure in the presence of formation flights. These requirements are in our opinion:

control of the mean cinematical behaviour of the entire formation,

detection of target movements deviating from the mean cinematical behaviour of the formation.

In order to fulfill these requirements we considered it unnecessary to control each individual target movement within the formation. We tried, therefore, to track the formation targets jointly instead of individually. Similar considerations can be found in (Flad, E., 1977; Taenzer, E., 1977), but both authors do not renounce single target tracking with the inner formation targets. Our approach, called Formation Tracking, is based on two control principles:

Central track control,
marginal track control.

The central track's state variables describe the mean cinematical behaviour of the tracked formation. In case of almost parallel target trajectories (see definition of the "dense-target"-situation) the correspondence between the formation targets' motion characteristics and central track description is quite exact. The correspondence becomes weaker if single targets or a group of targets accomplish deterministic deviations from

the parallel movement. We are especially interested in the detection of targets which are on missions different to the rest of the formation.

Marginal track control serves the maintenance of target tracks manoeuvring away from the formation (divergence) and tracks joining the formation (convergence). Marginal tracks represent targets which are situated at the flanks of the formation (with regard to a given cartesian tracking coordinate system; see, for instance, Figure 4). Relevant variations of the marginal tracks in relation to the central track and variations of the target numbers indicate divergent or convergent target movements which demand suitable reactions.

FORMATION TRACK INITIATION

One of the problems we were confronted with in course of the realization of the formation tracking procedure was the problem of formation track initiation. Formation track initiation has to decide upon which targets should be tracked individually and which targets should be tracked as a formation. Furthermore, formation track initiation should supply the system with initial information about position and spatial extension of the formation.

If we take only search plots into consideration the first problem can be solved by comparing the distances of successively arriving search plots with the minimum target distances d_{min} which result from a given small probability of miscorrelation P_{mc} (Fig.3). Within a fixed scanning time interval T this distance test decides whether a search plot should initiate an individual track or should be combined with other search plots in order to build up a formation track germ. The time difference T between the arrival of the search plot and the start of an initiation process depends on the time necessary to scan a certain environment of the search plot and the time the expectation gate is permitted to grow without going beyond a reasonable limit of size. This limit should not be exceeded in order to avoid disturbances of the initiation process. A formation track germ is built up by the arithmetic mean (central position indicator) and the extreme values of the position coordinates (e.g. x_{min}, x_{max}) of the integrated search plots (Figure 4). Additionally, the number of the integrated search plots should be determined for later application.

The distances between an established formation track germ and neighbouring search plots should be large enough to allow nearly conflict-free initiation (Figure 2). So - in this case - the distance-criteria have to be changed.

The distance test is quite similar to the search-plot identity-test which has in any case to be executed in computer controlled tracking. The identity-test decides whether an incoming search plot belongs to a known track or is the beginning of a new track. Because of this similarity the problems of identity and dense neighbourhood can be solved in the same way (radar sort box etc.). Figure 5 shows a flow-diagram of the identity-test and the neighbourhood-test both of which have to be executed after the arrival of a new search plot. The tests have to take into account the position information of all existing search plots, tracks, and formation tracks.

FORMATION TRACK EVOLUTION

According to the principles of computer controlled tracking the formation track germ established within formation track initiation will be scanned individually by track orders. The formation track germ is represented by a rectangular parallelepiped with faces parallel to the given cartesian tracking coordinate system. The description of the formation track as parallelepiped will be maintained throughout the life time of the formation track. There may be weaker and stronger possibilities of the mathematical description of the structure of the tracked formation, but in our opinion the parallelepiped has especially in connection with the cartesian tracking coordinate system the advantage of simple mathematical tractability. The extension of the parallelepiped eventually exceeds the beam-width of a single track beam. In this case the formation track germ has to be scanned by a sequence of track beams which are ordered nearly simultaneously and cover the parallelepiped completely. The resulting pattern of track beams (Figure 6) looks like the search pattern of the phased array antenna system and allows to minimize the number of undetected targets with a given small number of multiple detections of the same target.

The resulting track plot cluster has to be correlated with the formation track germ. The arithmetic mean of the position values and extreme values in each coordinate have to be determined.

These cluster values will be filtered with the appropriate track germ values in order to get the actual filtered position values of the formation track parallelepiped (i.e. central position indicator, marginal positions x_{min}, x_{max} a.s.o.). The application of Kalman filters (independent in each coordinate of the cartesian tracking coordinate system) supplies the system with estimated position-, velocity-, and acceleration-values of the central track and the marginal tracks. The estimation of position, velocity, and acceleration allows to predict the future position of the formation track parallelepiped and, therefore, forms the basis of the next scan.

Marginal target tracking in decoupled cartesian coordinates is quite reasonable, because generally only one coordinate per marginal target is processed and different targets may be situated at each face of the parallelepiped. The statistical and cinematical parameters of the applied Kalman filters are similar to those used in single target tracking; slight modification may be necessary due to the special error distribution of the mean position data and an abnormal cinematical behaviour of marginal tracks. Such an abnormal behaviour may appear, when marginal targets are replaced by inner targets.

DIVERGENCE- AND CONVERGENCE CONTROL

In order to detect divergent (Figure 7) and convergent (Figure 8) target movements the permanent control of plot distances and target numbers within the formation would be necessary. This control process would involve a lot of computer time and -storage. We, therefore, restrict our attention to those divergence- and convergence-processes which directly influence the marginal targets of the formation.

By controlling only the spatial extension and the target numbers of the formation the most relevant cases of divergence and convergence (formation track splitting, formation track junction) will be detected. But the control of the formation size in an antenna fixed cartesian tracking coordinate system does not allow an unambiguous distinction between manoeuvres of the entire formation and real divergence- and convergence-processes. In both cases the size of one or more faces of the formation parallelepiped will change. The control of formation size should be executed, therefore, in a central track orientated cartesian coordinate system (i.e. The x'-y'-system in Figure 9).

The first step in the control process is the estimation of the formation size, i.e. the mean distances of the extreme position values of correlating plots in each coordinate of the central track orientated system. The target number within the formation, given by the mean number of correlating plots, is determined simultaneously. Then the sample values of formation size and plot numbers appearing at each scan are permanently compared with the estimated values. In case of disagreement statistical decision procedures are applied in order to separate statistical (false alarms, missing plots) and deterministic variations of the control variables.

The outcome of these decision procedures decides upon further activities, which will have to be accomplished with the tracked formation; e.g. assimilation of other tracks (convergence), complete or partial splitting into single tracks or smaller formations (divergence).

The splitting activity uses the target distances (represented by track plot distances) and given distance criteria in order to determine the substructures (single targets, smaller formations) which afterwards will independently be tracked. The splitting activity, therefore, has great similarity to the formation track initiation procedure. In order to relieve the continuation of the tracking process the generated substructures should be supplied with initial state information derived from the motion characteristics of the dissolved formation.

CONCLUSIONS

The proposed procedure of Formation Tracking is intended to be an alternative to single target tracking in case of extremely close spaced targets.

It is to our knowledge the first completely automatic procedure which gives up single target tracking in case of formation targets and prefers a more collective method of target data processing. The separation of the problems "tracking in dense clutter environment" and "tracking in dense target environment" necessitates the systems's ability of recognizing, whether a search plot cluster eventually originates from dense clutter instead of a target formation (Fleskes, W., 1978).

The tracking- and control-procedures of Formation Tracking were first developed and tested within a one-dimensional simulation of the appropriate airspace situations. Examples of the tests are demonstrated in Figure 7 and Figure 8: target divergence and target convergence resp. Five targets are simulated (close curves in position-time representation), the appropriate tracks are represented by vectors (head ≙ filtered position, arrow ≙ filtered velocity). Formation tracks are represented by three vectors appearing simultaneously (central track and marginal tracks). Single target tracks are generally tracked at different points of time.

These tracking- and control procedures will be transfered with small modifications to our three-dimensional radar data processing system (ELRA). We expect that Formation Tracking especially for target numbers n>3 will require less computational effort than any attempt of single target tracking in case of formation targets.

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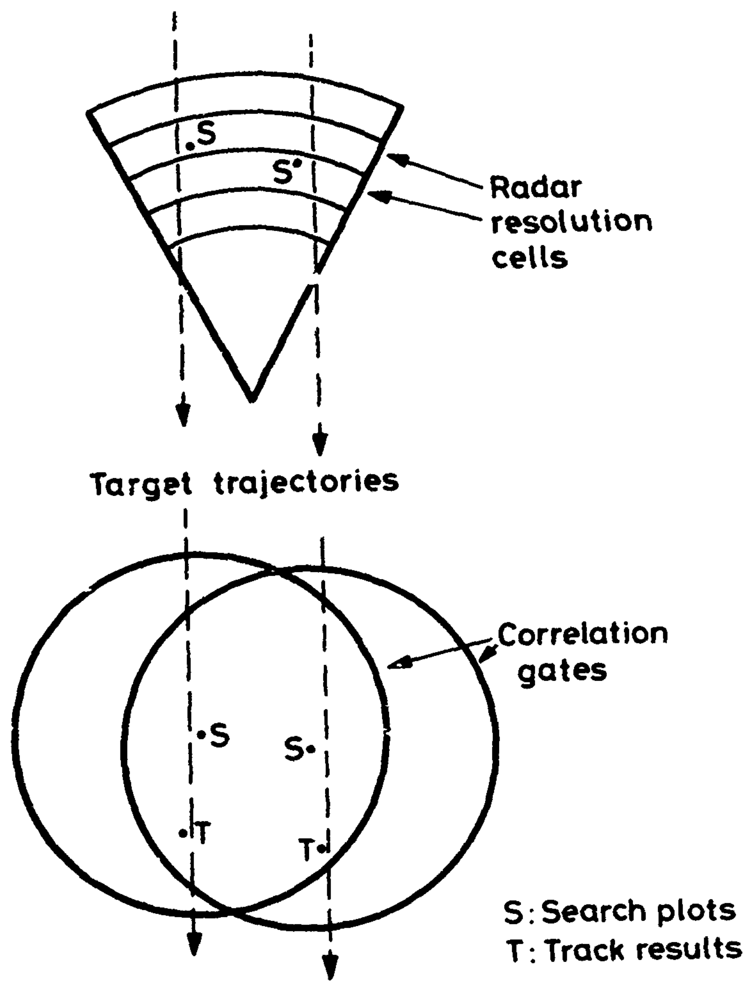


Fig.1 Correlation-conflict (track initiation)

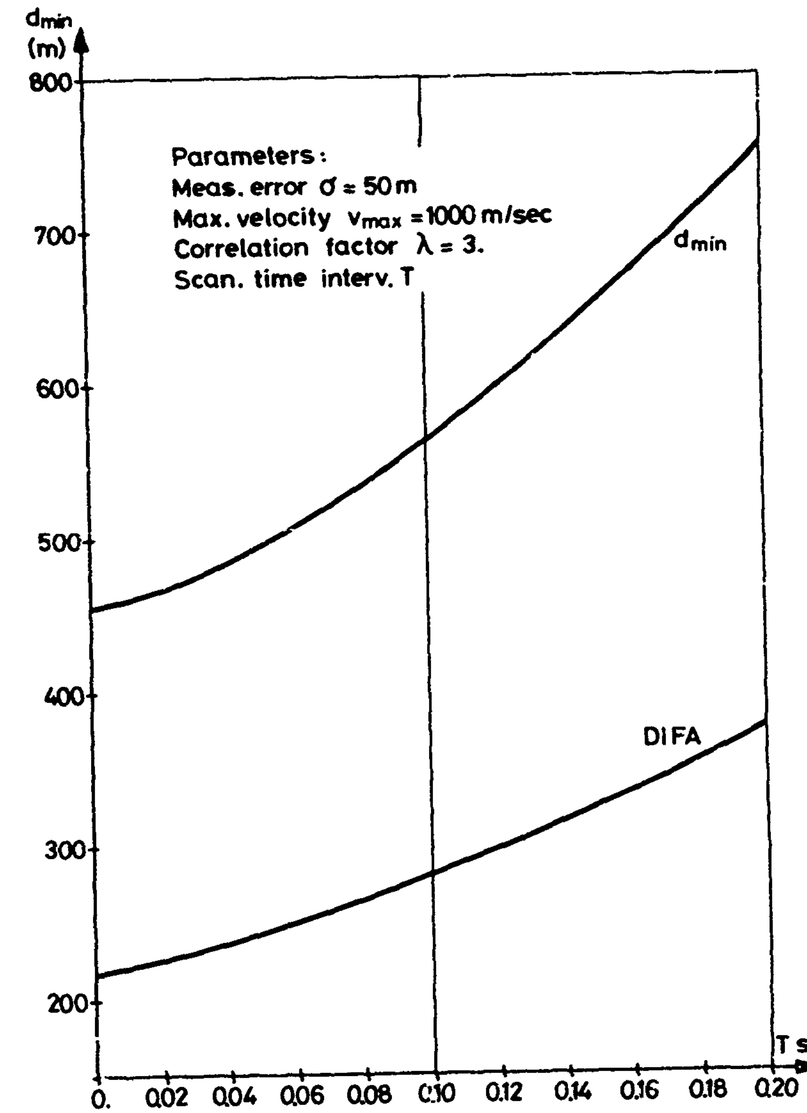


Fig.2 Minimum target-distances d_{min} for a given conflict-probability $P_c = 0.001$ (track initiation)

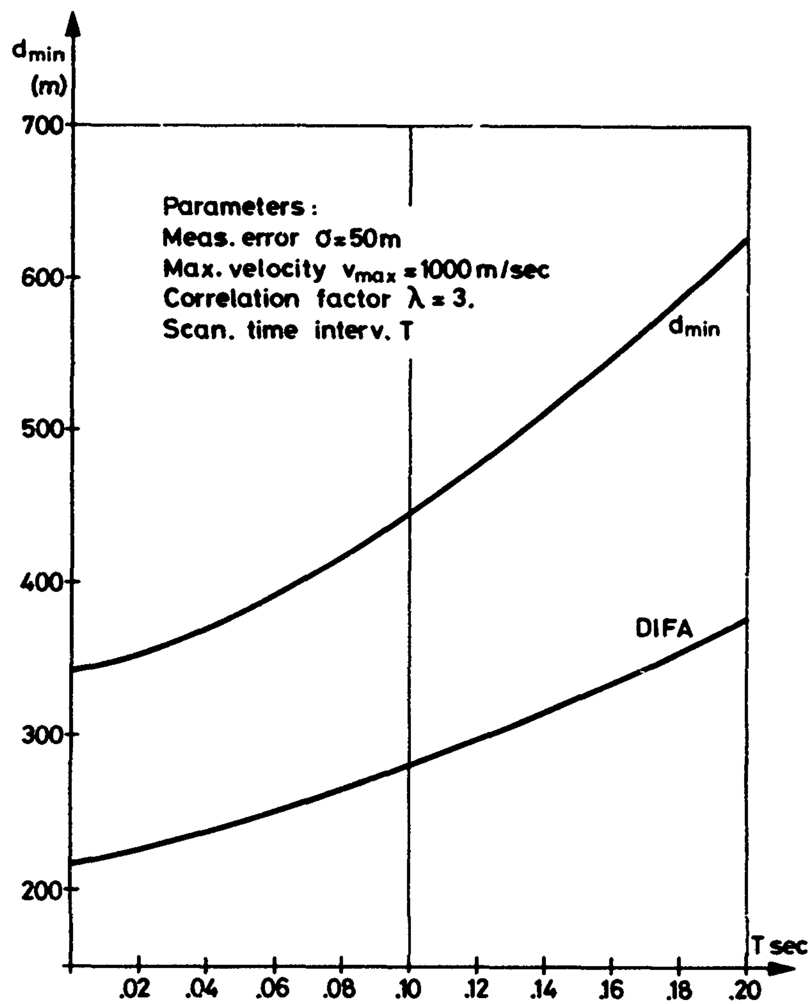


Fig.3 Minimum target distances d_{min} for a given miscorrel.-probability $P_{mc} = 0.001$ (track-initiation)

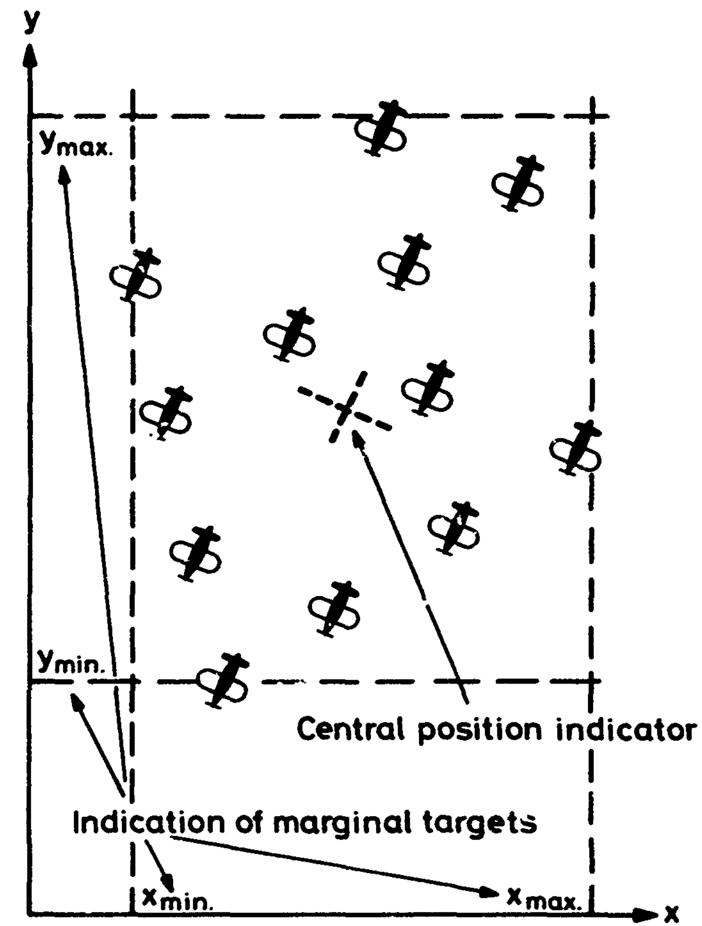
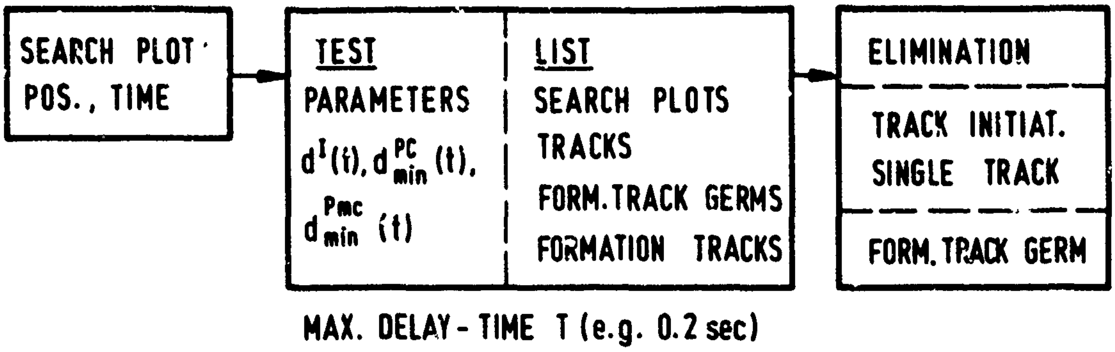


Fig.4 Formation flight representation



IDENTITY - AND DISTANCE - TEST

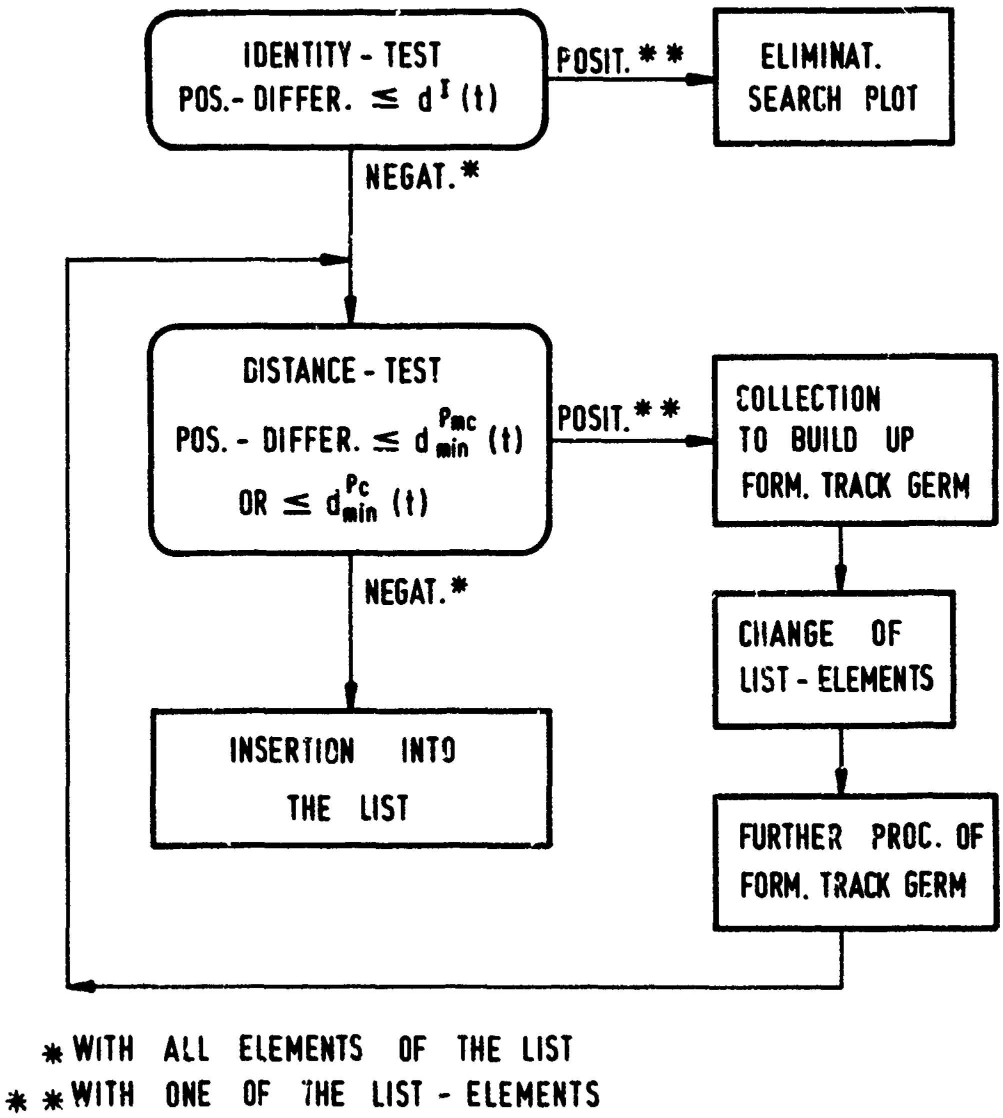


Fig.5 Schematic flow-diagram of formation track initiation

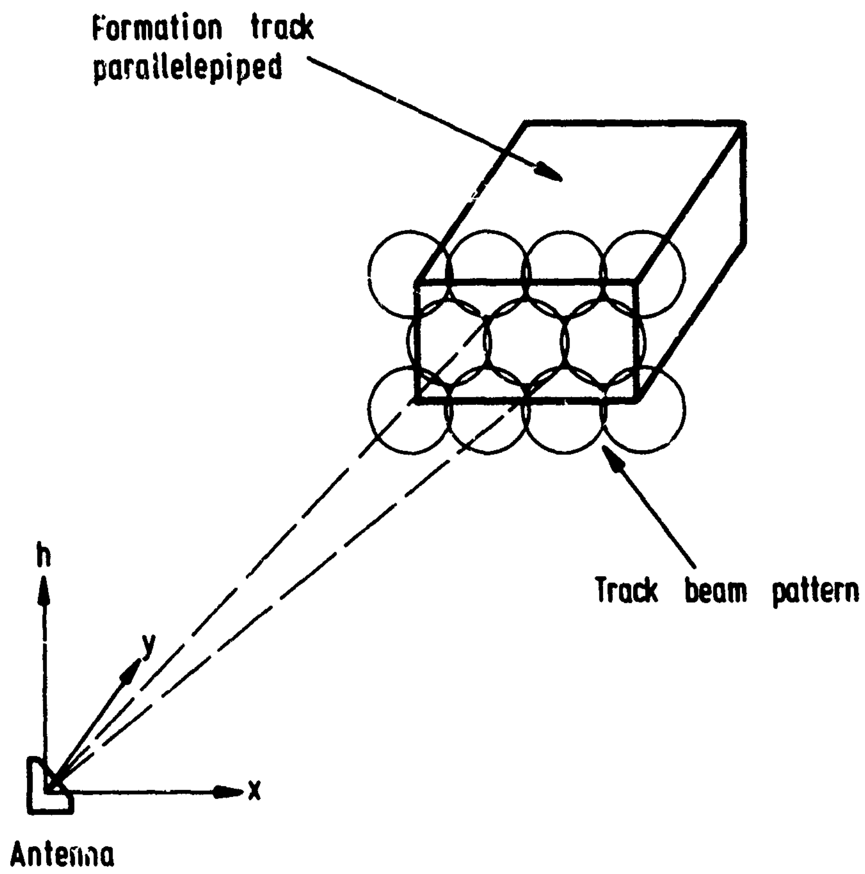


Fig.6 The track beam pattern used to scan the formation parallelepiped

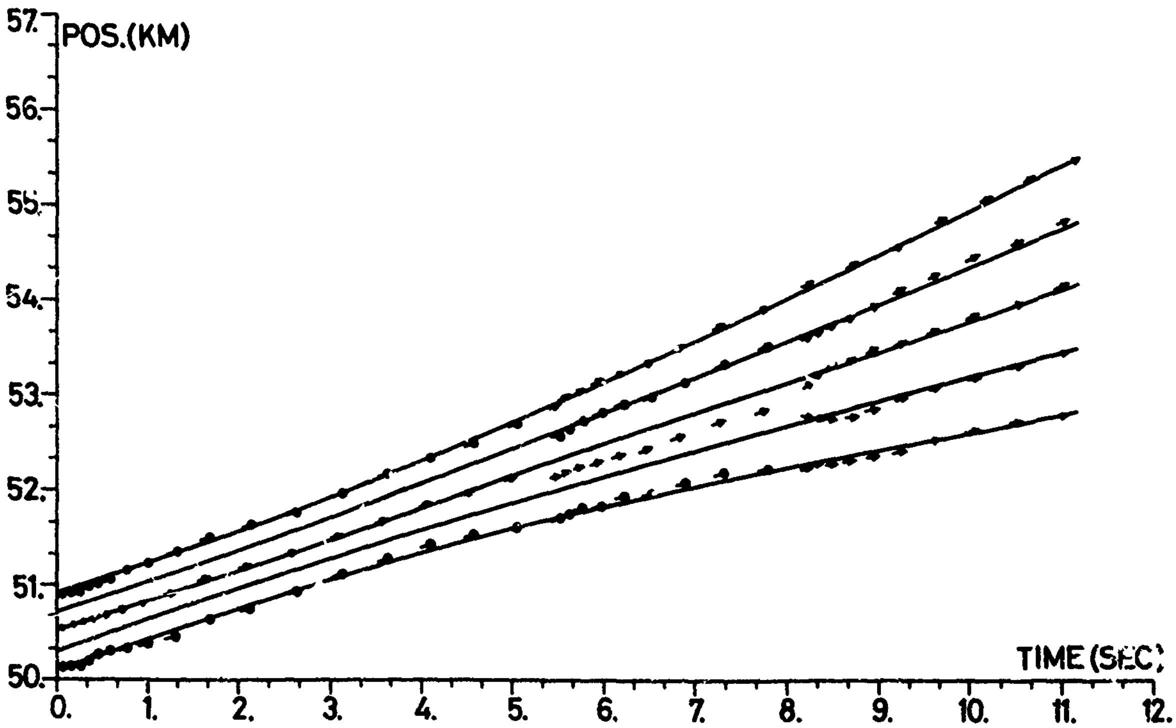


Fig.7 One-dimensional example of formation track splitting

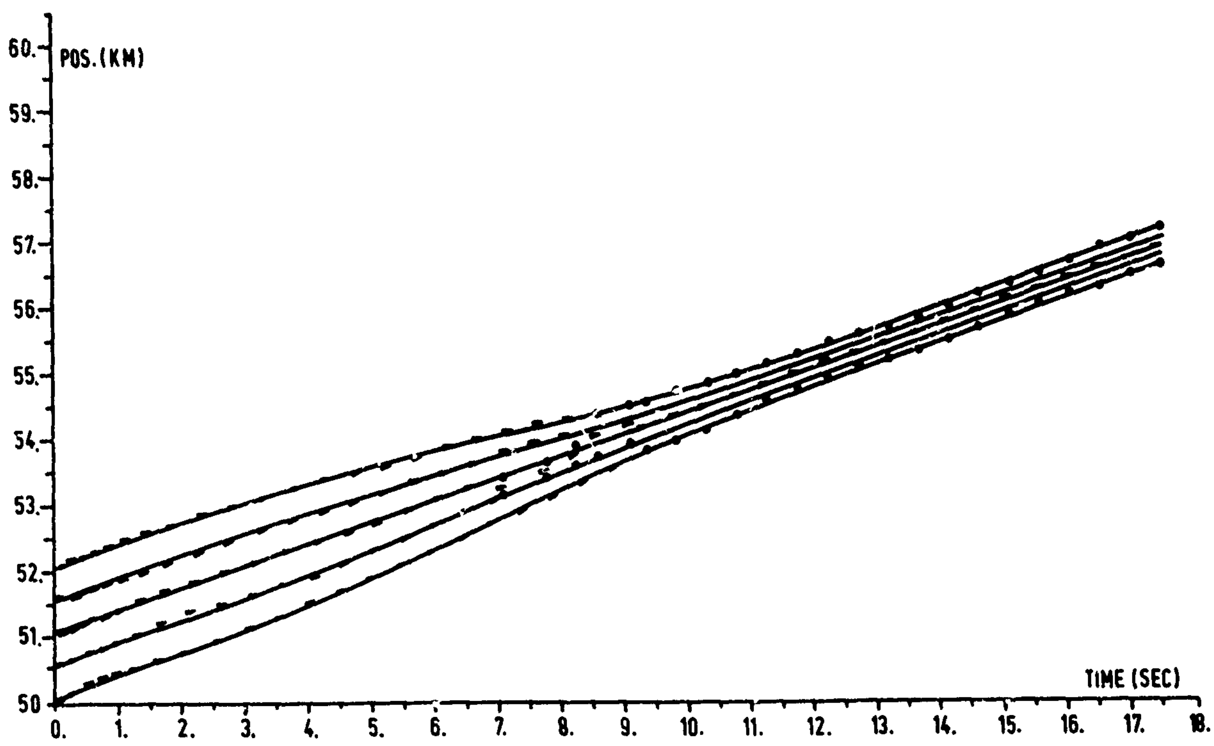


Fig.8 One-dimensional example of formation track junction

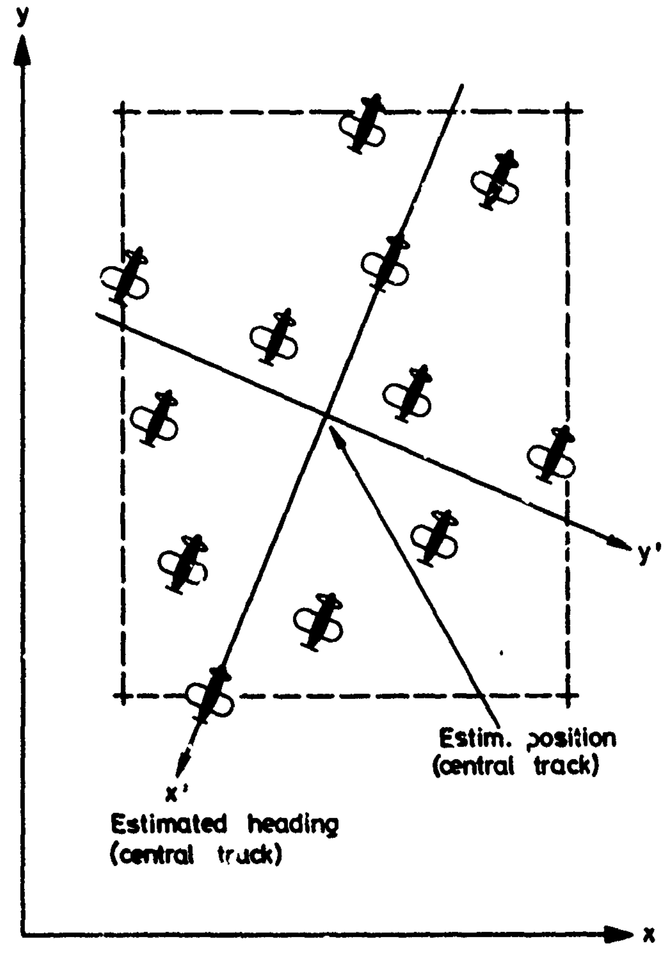


Fig.9 The central track orientated co-ordinate system

DISCUSSION

D.B.Reid, USA

What is your fundamental reason for creating formation tracks? Is it because of (a) sensor resolution; (b) an inability to associate tracks with returns; or (c) merely a desire to save computer space?

Author's Reply

It is the inability to associate tracks with returns and, of course, in order to save storage and computer time as well.

F.Herzmann, FRG

For what number of targets flying in formation is your tracking procedure more efficient than separate target tracking?

Author's Reply

For three targets.

E.Taenzer, USA

What do you do about redundant tracks that come about by the merger of tracks that approach each other, so that their targets fly in formation?

Author's Reply

We try to avoid redundant tracks by testing the identity of tracks before initiating them.

PERFORMANCE OF AUTOMATIC TRACK INITIATION LOGIC IN SPECIFIC TARGET ENVIRONMENTS

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SUMMARY

Two generalized analytical computer models were developed to provide data for a parametric assessment of various ATI algorithms which attempt to replicate the surveillance operator's judgmental processes. One model was used to investigate the initiation of tracks on actual targets and the other was used to determine the track initiation performance based only upon false reports. It has been determined that this performance dichotomy is valid for the anticipated NAEW target environment.

The results of the investigation indicate that there are several ATI algorithms which would yield satisfactory performance. Even within this set of acceptable algorithms, however, some criteria provide enhanced performance in initiation of true targets at the expense of a relatively larger number of false track initiations and there are others for which the converse is true. Furthermore, the level of false target reports per scan, the expected target speeds, and the speed with which real targets are initiated are all significant factors in the construction of the ATI feature and their ramifications are discussed in detail.

1. INTRODUCTION

1.1 PURPOSE

The inherent physical limitation of the number of surveillance operators available for any command and control system can result in significant operator workload and stress as the number of radar target reports increases due to better radar coverage and increased target densities. Some of this burden can be reduced by effective computer processing to relieve the operators of as many repetitive tasks as possible. In particular, for systems in which a computer tracks targets and presents the operator with a display of the track characteristics, the automated surveillance functions can be extended by having the computer detect the existence of an untracked aircraft and establish a track on that target.

This implies than an automatic track initiation (ATI) capability is desirable if it reduces the operator workload. This necessitates a surveillance radar with an adequately low false report rate and an ATI implementation which precludes off-setting problems in terms of establishing false tracks on spurious targets or low quality tracks on marginally detectable targets. Taking these considerations into account, the purpose of this study effort was to determine which initiation algorithms will provide acceptable performance for the NATO Airborne Early Warning (NAEW) aircraft under expected operational conditions. To accomplish this goal, an analytical technique was devised whereby insight could be gained regarding the sensitivity of ATI algorithm performance as a function of the parameters of the tracking process, the environment, and the initiation criteria.

1.2 GENERALIZING THE RESULTS

The computer models employed in this investigation were purposely constructed to avoid effects related to specific radar characteristics or unique tracking techniques. The parametric results can therefore be generalized and extended to any track-while-scan surveillance system without regard to scan rates or other system characteristics.

Examination of some of the complex ATI-related issues, such as might be encountered in certain scenarios with a particular juxtaposition of targets, would best be accomplished with a Monte Carlo simulation approach. However, the structure of the analytical models developed in this study provides a means of rapidly evaluating initiation strategies and also provides a significant cost savings relative to the simulation technique. The models also eliminate the effects of statistically anomalous situations and yield mean or expected performance values.

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2. COMPUTER MODELS

In a track-while-scan system, the process of automatically generating a track requires the association of radar reports on sequential scans or observations. Therefore, the initiation strategies investigated involve the rate of successful correlation of radar reports and possible tracks and a track is established when it satisfies several criteria related to the correlation rate.

In order to derive the relationship of the performance of various initiation logics as a function of system and environmental parameters, it was necessary to first define the measure of performance. Two figures of merit were postulated: one is the mean time to establish a track based entirely on true radar reports and the other is the time required to establish a track based on radar false alarms. It was determined that for a low density false alarm environment these two factors can be considered independently; thus it was possible to develop two separate analytical computer programs.

Both computer models have been generalized to eliminate the specific effects associated with the performance of a particular radar or the peculiarities of the computer tracking algorithms. In this manner the target environment can be specified, the track initiation criteria can be established, and the characteristics of the system can be defined by means of parameters relevant only to the ATI process. The delay in establishing a valid track, once the target enters the surveillance volume, and the rate of false track initiations can then be determined as a function of all of these factors.

The canonic form of the track initiation algorithm has three distinct phases in the process with each track designated as either potential, tentative, or established depending upon its status. In each of these phases each track progresses through a series of states as a function of its radar history. A potential track is one which has only a single detection by the radar. Thus, there exists no information regarding the target's speed or direction. A tentative track is one which has had more than one correlation but for which there is not enough data to either ensure a high quality track or to have a high confidence level of the track being a true track. An established track implies a track with a high confidence of representing a true target.

Since the initiation criteria under consideration were all related to the sequential occurrence of radar observations, it was possible to structure the models as finite state Markov processes. An uncorrelated radar target report was considered to be a potential track and the occurrence or absence of subsequent correlating reports would determine whether or not the track would advance to any other particular state. A correlation of a track and a radar report was termed a "hit" while the lack of such a correlation was termed a "miss". The track initiation criteria were then based on the hit/miss sequences and the track moved from one state to another depending on whether a hit or miss occurred on each radar observation.

The system characteristics are accounted for in the state transition matrix (which defines the likelihood of a track hit or miss) and the independent variables are related to the target environment as specified by the target probability of detection and by the false alarm density. The results of the investigation are average values representative of general conditions rather than the results of a single specific case which might be obtained from a tracking simulation.

2.1 VALID TRACK MODEL

The form of the valid track model is shown in Figure 2-1 with, in this illustration, each track being in one of seven possible states: targets in the null state (State 1) are those undetected by radar or dropped by the ATI logic, the potential phase (State 2) represents a single detection, the tentative phase (States 3, 4, 5, and 6) includes those targets which may either be promoted into the final established phase (State 7) as a system track or which will be dropped back to the null state depending on the sequence of radar observations. The solid lines in the diagram indicate a transition between states which occurs if there is a radar "hit" and the dashed lines indicate the transition given a radar "miss". For the particular model illustrated, to establish a system track two consecutive hits are required to reach tentative status and then any combination of two hits in the next three observations will result in the promotion to established status. A miss prior to attaining tentative status or two misses while in the tentative phase will be sufficient to drop the track back to null state. In any event, for this algorithm, the track can only stay in the ATI process for a maximum of five scans before it is either established or dropped.

The valid track model is not dependent upon the tracking program, the correlation window size, or on any other system characteristics. The major independent variable is the probability that a track will correlate with a report and therefore all components are subsumed into the probability of detection (P_d) values established in the transition matrix. The structure of the transition matrix is determined by the number of states in the system and the values in the matrix are established by the system characteristics. An N state algorithm requires an NxN transition matrix, T, wherein the values

$$t_{i,j} = \begin{cases} p; \text{ if a track in state i goes to state j upon a hit} \\ q = (1-p); \text{ if a track in state i goes to state j upon a miss} \\ 0; \text{ otherwise} \end{cases}$$

Should the system characteristics be modified, it would be equivalent to altering the P_d values in that matrix. There is no dependence on the frequency of observations and consequently, if a scanning radar is assumed, the radar scan rate is not a factor.

A state vector representing the expected percentage of tracks in each state of the model following each iteration, or scan, was constructed along with a transition matrix which delimits the transitions between states. The model is initialized with 100% of the tracks in the null state and the model is operated until a desired number of tracks, e.g., 50%, 90%, 99%, etc., are in the established state.

The results plotted in Figure 2-2 depict the relationship between the target probability of detection and the number of scans required to initiate system tracks on 90% of the targets as a function of four representative initiation algorithms. The most rigorous logic requires two consecutive correlations to become tentative and then five hits in six scans during the tentative phase thereby taking an extremely large number of scans to achieve the desired level of performance at the lower values of probability of detection. Conversely, for any given P_d, the logic which requires only one correlation in three scans to achieve tentative status and then only one more hit in the next three scans to attain the established status will provide the desired level much more quickly. The other two logics provide intermediate performance: both require two consecutive hits to reach tentative status, then one requires two hits in six scans in the tentative phase and the other is identical except that a track will revert to null state if three consecutive misses occur.

These plots, in Figure 2-2, are normalized by eliminating the minimum number of scans required by each algorithm. As an example, for the five hits in six scans logic it is not possible for a track to be established for at least seven radar scans following its entry into the surveillance volume and therefore the plot in Figure 2-2 represents the number of scans beyond the minimum of seven.

2.2 FALSE ALARM MODEL

The model used to investigate false track initiations is illustrated in Figure 2-3. It is similar in form and function to the valid track model but the initial state now represents a false alarm generator or source. Since potential tracks consist of uncorrelated reports, a feedback loop is included to calculate the number of potential tracks in a scan. Specifically, the number of potential tracks equals the number of false reports per scan less the number of correlations for that scan. However, since radar reports tracks in this model are random and are not based on a detectable object, when tracks are dropped, they are not recycled into the model. For this study, the model is iterated until a single false track reaches the established state and the number of iterations is then the expected number of scans between false track initiations.

In the false track case the transitions between states, i.e., the hit/miss probabilities, are related to the number of false alarms per radar scan, the total surveillance area, and the area of the correlation window in the tracking algorithm. Assuming false alarms uniformly distributed in the surveillance volume, the probability that a false alarm will correlate with a track in the system is equal to the ratio of the correlation window area and the total surveillance area. The probability of any false alarm correlating with a track is that area ratio multiplied by the number of false alarms.

Figure 2-4 illustrates the expected number of scans, or delay, between false track initiations as a function of the number of false alarms (NF) for four typical track initiation logics. The logarithmic relationships emphasize the sensitivity of this model to changes in false alarm density and the slope of the lines is a function of the number of hits necessary to establish a track. These plots also indicate the discrimination against false alarms which can be achieved by requiring a larger number of correlating reports to establish a track by requiring several consecutive hits.

Using other false alarm discrimination techniques in the system would be equivalent to reducing the false alarm densities for this model. These techniques include:

(a) Using range rate information from the initial radar reports if available. This would provide a coarse discrimination which could also exclude consideration of out-bound targets or low-speed targets or targets moving tangentially with respect to the radar.

(b) Shaping the correlation window. A circular window for the first correlation provides no preference towards or discrimination against targets moving in a particular direction. Shaping the window and reducing its area to bias the correlation in favor of targets with a particular velocity will also reduce the probability of correlation with a false alarm.

(c) Activating the ATI function in only a portion of the surveillance volume. The probability of a false track initiation is reduced linearly as a function of the fraction of the area in which it is active.

The analytical model can accommodate the incorporation of any such features by accounting for their effect in the probabilities of correlation.

3. INTERPRETING THE STUDY RESULTS

The automatic track initiation models have provided insight into the relationship of the variables involved in the ATI process and they permit a rapid evaluation of the effect of modifying any of the several relevant parameters. The important factors must be balanced to achieve a proper level of performance of the ATI feature in the anticipated operational environment. The existing specifications might therefore be altered or an implementation may be selected which meets the current specifications but which emphasizes one particular characteristic more than another. These alternatives are discussed in detail below.

3.1 CONFIDENCE LEVEL

If a required percentage of targets must have tracks initiated within a certain period of time after entering the surveillance volume, the specification of that percentage (or confidence level) is a major consideration in designing the ATI algorithm. The logarithmic nature of the process requires that twice as many scans be allocated to achieve 99% confidence than are necessary to achieve 90% confidence for a given

initiation logic. At a given P_d reducing the required confidence level further would provide related reductions in the number of scans to reach that lower level.

This situation is illustrated graphically in Figure 3-1 where the expected initiation delay is plotted for 90% and 99% confidence levels for a logic which requires two hits in three scans to advance beyond the tentative phase. The most significant effect is evident at the lower probabilities of detection (P_d) because with a high P_d most targets will quickly become established. A corollary effect occurs when the specified confidence level is high, but the specified initiation delay is low, such as with 99% of all targets initiated within twenty scans and a $P_d = .4$; this specification necessarily imposes a less stringent initiation criteria which is likely to allow the formation of more false tracks than would a more rigorous algorithm.

3.2 FALSE ALARM DENSITY AND FALSE TRACK RATES

The results of the false alarm density studies which were presented in Figure 2-4 indicate the effect of specifying a false alarm environment which is greater than that expected under operational conditions. Although such a specification might provide some additional operational performance margin, it also restricts the set of possible initiation criteria because of the non-linear effects. Depending on the particular logic under consideration, specifying a false alarm density five times as large as the nominal expected value will result in a change of mean time between false tracks by a factor of between 500 to several thousand.

Furthermore, restricting the rate at which false tracks are established to a value which is overly conservative in an operational sense will have an impact on the delay in valid track initiations because a more rigorous initiation logic will be required. Again referring to Figure 2-4 if a false alarm density is specified as 100 false alarms per scan and the specified mean time between false track initiations is reduced from 1000 scans to 100 scans then the selected logic can be changed from 2 hits in 3 scans to 2 hits in 6 scans. From Figure 2-3 it can then be seen that the delay in establishing 90% valid tracks will drop from 55 scans to 29 scans at a probability of detection of .4.

3.3 CORRELATION WINDOW AREA AND TARGET SPEED

A simple tracking logic will predict the expected position of a target and will accept a radar return within some distance of that predicted position as the basis for the subsequent prediction. The area within which a return is accepted as a valid target report is the correlation window and its size is a function of the expected target characteristics, the sensor performance, and the tracking logic performance.

Because little, if any, information relating to target speed and direction is contained in the first radar report, the correlation window is generally a circle with a radius determined by the specified maximum detectable target speed and the radar scanning rate. For a target speed of 1800 knots and a ten second scan interval, the window would have a five nautical mile radius while a target speed of 600 knots would require a window of radius 1.7 nautical miles. In this example, specifying the greater target speed, if it is not actually required in an operational circumstance, would have a secondary effect of increasing the probability of a false alarm correlation by an order of magnitude with a concomitant increase in the rate of false track initiations because the probability of a false alarm occurring within the window is a function of the radius squared.

The relationship between the false track initiation rate and the correlation window radius is depicted in Figure 3-3 for four initiation logics and a specific false alarm density. As an illustration, approximately 400,000 scans would be required to initiate a false track if a circular correlation window with a two mile radius were used with the 2 of 6 logic, but a five mile window with that same logic would reduce the interval to less than 7,000 scans.

A more complex tracker algorithm will use a variable or adaptive window which is modified as a function of the correlation history. Thus the large window is necessary for the initial correlation due to the lack of information, but as more reports correlate with the track the prediction of the target position is refined more accurately and the window size can be reduced; however, should correlations be missed the window size would increase. The variation in correlation window area can be accommodated in the false track model by inserting the appropriate probability values in the transition matrix. Figure 3-3 illustrates the number of scans for three logics to establish a single false track as a function of correlation window radius when the false alarm density and the surveillance volume remain constant. Figure 3-4 shows the relative performance of two logics when a constant three mile window is used in comparison to the same initiation algorithms when a six mile window is employed for the initial correlation and a two mile window is used subsequently. From these plots it can be determined that the variable window tracker exhibits the characteristic of an equivalent constant "effective" window of less than 3 miles.

The adaptability of the correlation window provides a compromise between the higher false track initiation rate and the need for tracking high speed targets. However, if reports are missed on consecutive scans it is likely that the window area will increase to account for prediction uncertainty and error. The effect of the growing window is shown in Figure 3-4 where the logic requires only one correlation in three scans for a track to reach the tentative phase. Since no information on target velocity is contained in the first (potential) report the correlation window radius increases from six miles to twelve miles to eighteen miles on subsequent scans if there is no radar hit. Once into the tentative phase, the tracking logic reverts to a two mile radius window.

The parameter of interest in all of these cases is the area of the correlation window (independent of its geometrical shape) so that if only radially entering targets are of operational concern, the window shape might be semi-circular and these plots would still be applicable.

4. CONCLUSIONS

The evaluation of the results from the computer models indicates that there is no single, optimal ATI algorithm. Rather there are a number of alternatives which are more or less useful depending on the operational requirements and contingencies. As an example of the situation-dependence, an environment with slow targets having a high probability of detection and a high false alarm rate can use a more stringent initiation criteria in order to mitigate the effect of the false alarms. On the other hand, an environment with fast targets having a low P_d and a low false alarm rate will necessitate quick track initiation with little regard for false initiations. The logarithmic sensitivity of the scoring logic to the target P_d and to the false alarm density makes it difficult to span a range of multiple requirements.

Given these considerations, it would be appropriate to have the initiation function implemented in a manner which facilitates modification of the initiation criteria in response to changing operational demands. If the hit/miss characteristics or the transition matrix were coded into a computer program as changeable variables, then such modifications could be accommodated.

The selection of the actual algorithms to be employed can be facilitated by using the models described in this paper. Even though the models do not consider the interaction or reports from different sources in the creation of tracks, they do provide an economical mechanism for evaluating performance and for selecting promising algorithms for further study.

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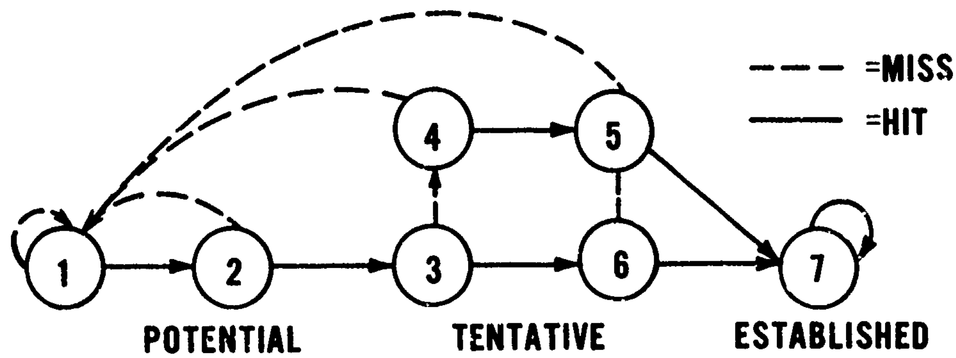


SCAN/STATE VECTOR

	1	2	3	4	5	6	7
0	1	0	0	0	0	0	0
1	q	p	0	0	0	0	0
2	$qp+q^2$	qp	p^2	–	–	–	–
.							
.							
.							

TRANSITION MATRIX

	1	2	3	4	5	6	7
1	q	p					
2	q		p				
3				q		p	
4	q				p		
5	q						p
6					q		p
7							1

Fig.2-1 State ıepresentation – valid track model

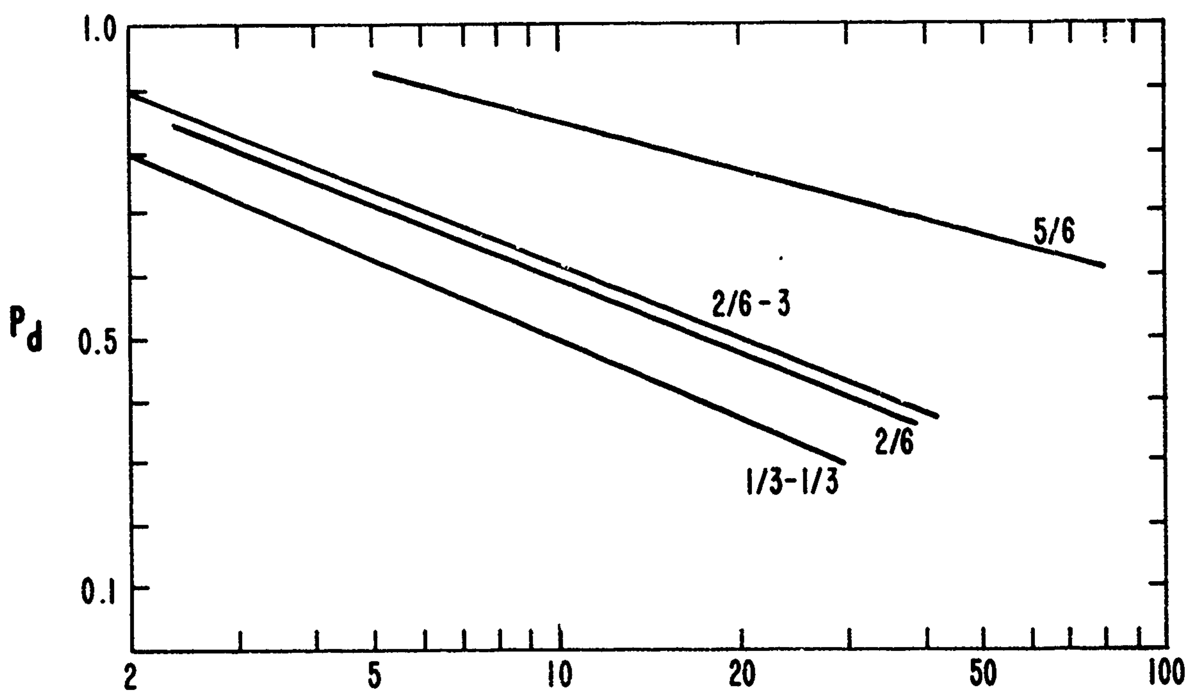
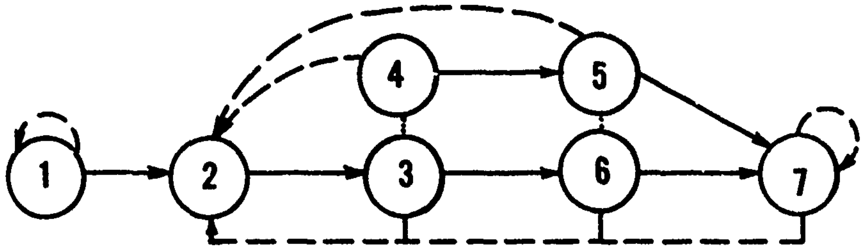


Fig.2-2 Number of scans to establish 90% valid track



SCAN/STATE VECTOR

	1	2	3	4	5	6	7
0	N	0	0	0	0	0	0
1	N	N	0	0	0	0	0
2	N	$N(1-p_1)$	Np_1	0	0	0	0
.							.
.							.
.	–	–	–	–	–	–	1

MATRIX

	1	2	3	4	5	6	7
1	1	1	0	0	0	0	0
2	0	$-p_1$	p_1	0	0	0	0
3	0	$-p_2$	0	q_2	0	p_2	0
4	0	$-p_2$	0	0	p_2	0	0
5	0	$-p_2$	0	0	0	0	p_2
6	0	$-p_2$	0	0	q_2	0	p_2
7	0	$-p_2$	0	0	0	0	1

Fig.2-3 State representation – false track model

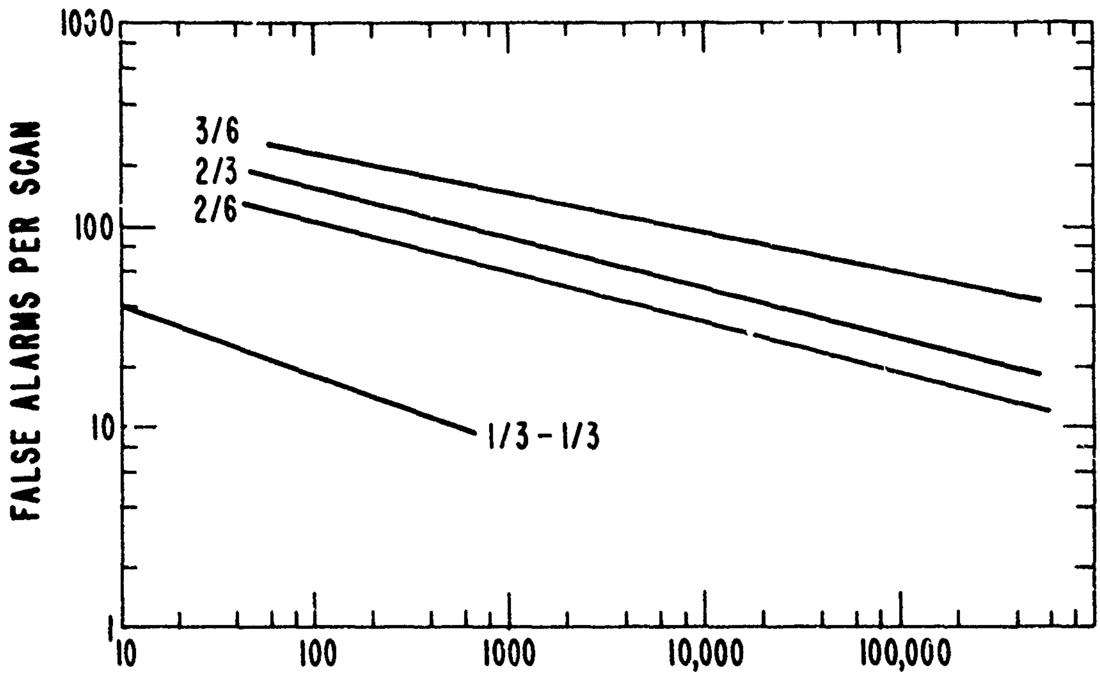


Fig.2-4 Sensitivity to false alarm density

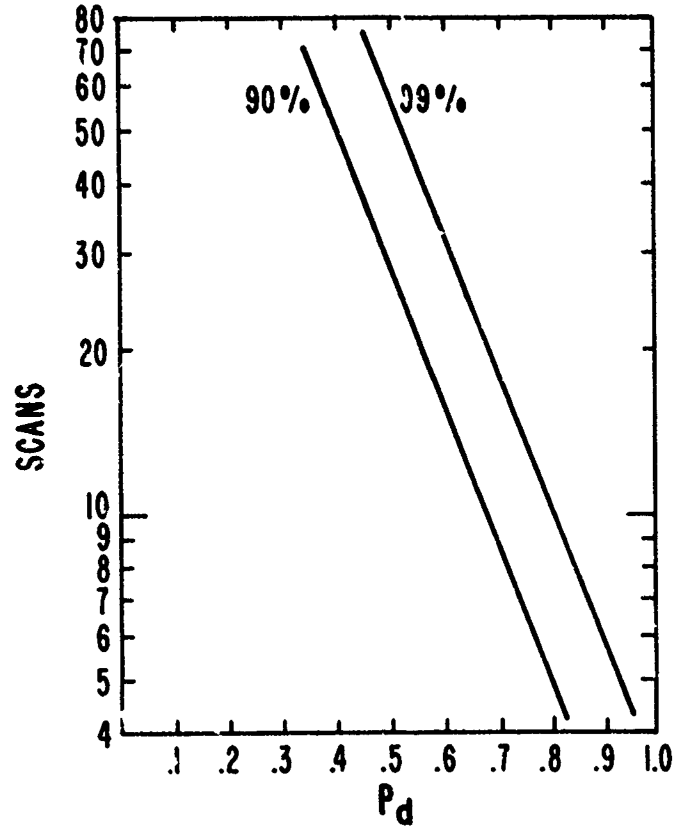


Fig.3-1 Number of scans to achieve required performance

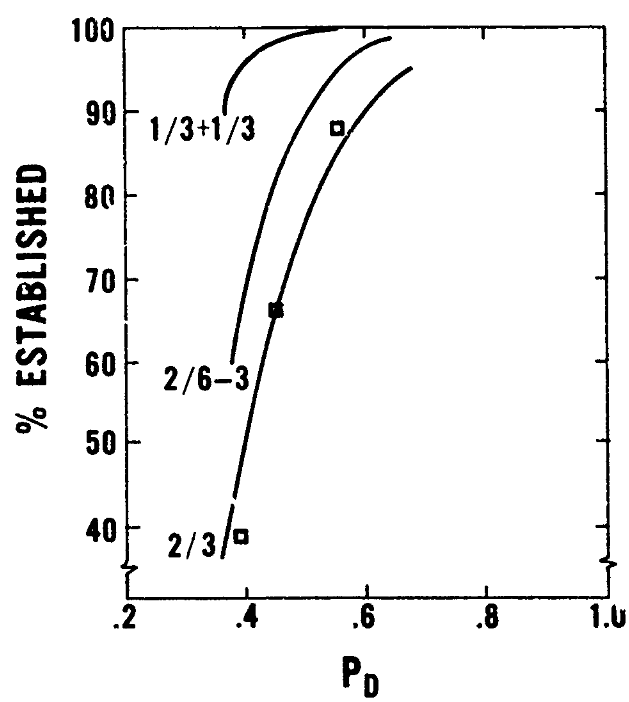


Fig.3-2 Performance after 18 scans

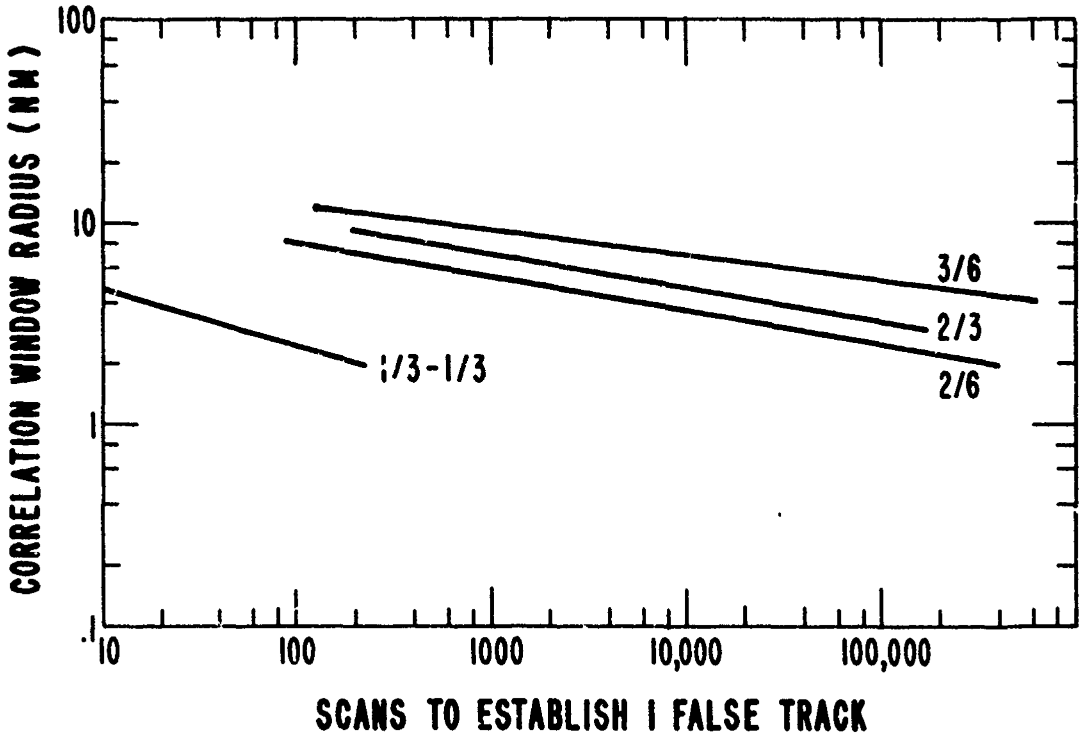


Fig.3-3 Sensitivity to window radius (NF = 50)

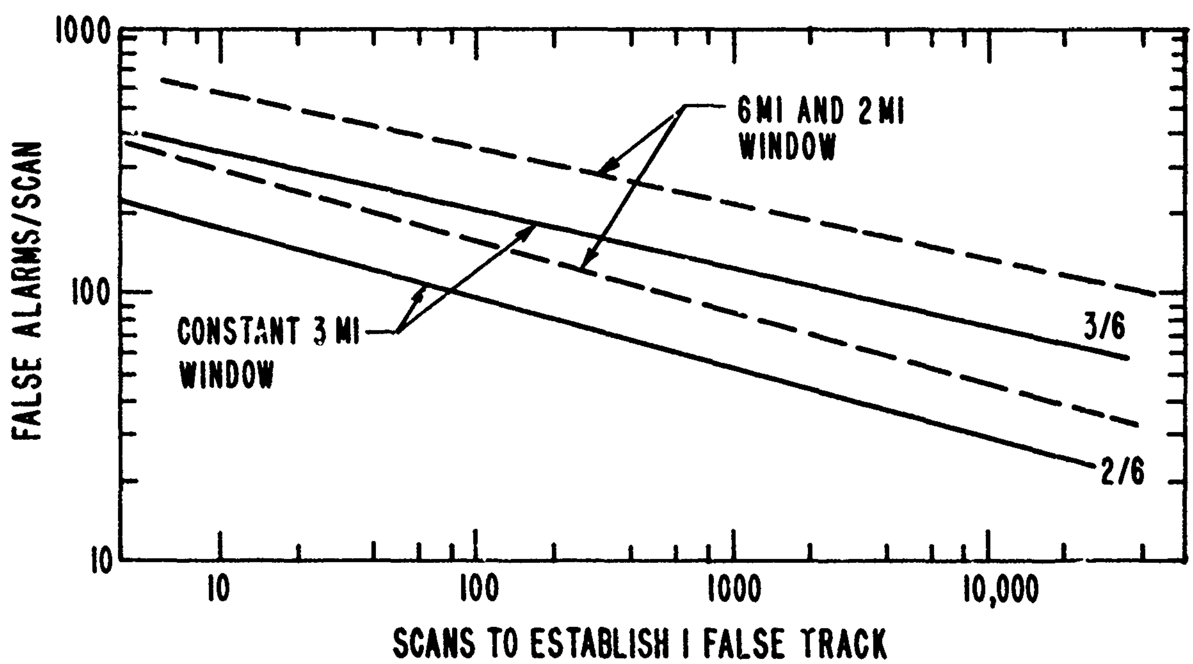


Fig.3-4 Improvement with adaptive window

DISCUSSION

S.J.Rabinowitz, USA

Did you consider varying P_d versus range in choosing the optimum logic?

Author's Reply

No, because that variation is scenario dependent. It could be done by changing the values in the transition matrix.

S.J.Rabinowitz, USA

Did you consider using varying number of false alarms versus azimuth choosing the optimum logic?

Author's Reply

No, the deterministic model is based on a uniform distribution.

R.M.O'Donnell, USA

The doppler response to the E-3A is varied due to its signal waveform. Do you plan to take this into account in your work?

Author's Reply

No, but it could be incorporated into the model as a modification of the values in the transition matrix.

INITIATION OF TRACKS IN A

DENSE DETECTION ENVIRONMENT

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ABSTRACT

In a dense detection environment present track-while-scan algorithms will inevitably introduce false tracks when processing is performed on a scan-by-scan basis. The maximum likelihood solution involving all detections on all scans is formulated and evaluated for the initiation problem. While the maximum likelihood method cannot be implemented because of the enormous computational requirements, it provides a standard to which more implemental algorithms (such as a raid detector, which is presently being studied) can be compared.

I. INTRODUCTION

Track-while-scan systems were first proposed for surveillance radars during the 1950's. If the probability of detection per scan is high, if accurate measurements are made, if the target density is low, and if there are few false detections, the design of the correlation logic and tracking filter is straightforward. However in a realistic radar environment these assumptions are never valid, and the design problem is complicated. This paper will consider the problem of track initiation in a dense detection environment. Since angle resolution is much poorer than range resolution, only range information will be utilized in this study.

In Fig. 1, there are three tracks and each track is detected five times. While it is obvious that there are three tracks present, many tracking systems would initiate incorrect tracks because they only associate the nearest detection with the predicted position of a tentative track and the predicted position of a tentative track with only 1 detection depends on a assumed velocity. Moreover, the situation in Fig. 1 rarely occurs; the situation in Fig. 2 being more common. Figure 2 is the same three tracks; however, several detections have been merged (i.e., individual targets are not resolved), three detections are missing, and two false alarms have been introduced.

The optimal solution of such problems has been generated under ideal conditions. Specifically, the maximum likelihood solution has been developed under the assumptions that the probability of detection, the probability of false alarm, the probability of target resolution as a function of target separation, and measurement error characteristics are all known a priori and that all targets are moving in straight lines. (A somewhat similar approach was used by Stein and Blackman [1975]; however, they did not consider resolution problems.) Even if all the above assumptions were true, the maximum likelihood method cannot be implemented in the foreseeable future because of the enormous computational load. However, it is still useful because it provides a standard with which to compare algorithms that can be more readily implemented.

There are two basic problems with the maximum likelihood method. The first problem is fundamental and concerns the tendency of the maximum likelihood method to indicate two tracks (with many unresolved detections) when a single detection is close to a single track. This problem was solved by penalizing tracks with unresolved targets or missing detections. A detailed description of the maximum liklihood method is given in Section II.

The second problem is the computational load. Since search techniques cannot be used to maximize the likelihood functions because of the large number of local maxima, the concept of a "feasible track" was introduced where a feasible track consisted of a specified number of detections lying within a specified distance of a straight line. Then the maximum likelihood of occurrence of each combination of the feasible tracks was evaluated. If there were N feasible tracks and one is interested in up to M track combinations, $\sum_{i=1}^{M} \binom{N}{i}$ likelihood functions would need to be evaluated. For instance, if N = 30 and M = 4, the number of likelihoods calculated is 31930. This problem is discussed in Section III.

A brief description of how the radar data is generated is given in Section IV, and the results of the maximum likelihood method applied to various target geometries containing from 1 to 4 tracks and several false alarms are given in Section V. Section VI suggests a practical solution which is presently being investigated and Section VII summarizes the results.

II. MAXIMUM LIKELIHOOD METHOD

The maximum likelihood method involves calculating the total probability that a given set of detections correctly represents a specified set of tracks. The probability of detection, the probability of false alarm, the probability of target resolution as a function of target separation, and the measurement error characteristics are all taken into account in the calculation of the likelihood. To facilitate the mathematical description of the likelihood method the following terms and definitions are used:

N_S = the number of scans

N_T = the number of tracks

N_D = the total number of detections

N_{FA} = the number of false alarms

N_M = the number of missed detections associated with the N_T tracks

N_{DR} = the number of detections involved in resolution problems (i.e., number of detections used in at least two tracks)

$N_{TR}(k)$ = the total number of tracks using the k-th detection which is used in at least two tracks

x_{ij} = the range of detection associated with i-th track on the j-th scan. If there is no detection associated (i.e., track has a miss associated), $x_{ij} = 0$

y_{ij} = the predicted range of the i-th track on j-th scan assuming a straight line trajectory.

All of the above variables are not independent. The following relationship holds:

$$N_D = N_S N_T - N_M - N_{TR} + N_{DR} + N_{FA}, \tag{1}$$

where $N_{TR} = \sum_{k=1}^{N_{DR}} N_{TR}(k)$.

The difference between predicted and measured position is assumed to be Gaussian distributed with zero mean and a variance of σ^2. Thus,

$$p(x_{ij}-y_{ij}) = \frac{1}{(2\pi\sigma^2)^{1/2}} e^{-(x_{ij}-y_{ij})^2/2\sigma^2} . \tag{2}$$

For later use, it will be convenient to introduce the expression

$$f(x_{ij}-y_{ij}) = \begin{cases} 1, & x_{ij} = 0 \text{ or } x_{ij} = x_{\ell j} \quad i \neq \ell \\ e^{-(x_{ij}-y_{ij})^2/2\sigma^2} & \text{otherwise} \end{cases} . \tag{3}$$

Assuming the probability of detection P_D is known, the probability of obtaining the specified number of detections is

$$\binom{N_S N_T}{N_M} (P_D)^{N_S N_T - N_M} (1 - P_D)^{N_M} . \tag{4}$$

The probability of not resolving any $N_{TR}(k) = N_k$ tracks which use a common detection x_k is calculated by first ordering the predicted positions, so that

$$y_{i_1} \leq y_{i_2} \leq \cdots \leq y_{i_{N_k}} ,$$

where for notational convenience the subscript of the scan has been dropped. Letting $D_\ell = y_{i_\ell} - y_{i_{\ell-1}}$, the probability of not resolving any N_k tracks is given by

$$P_R(x_k) = \prod_{\ell=2}^{N_k} P(D_\ell) \tag{5}$$

where the probability of not resolving two tracks separated by distance D (discussed in Trunk [1977]) is given by

$$P(D) = \begin{cases} 1 & D \leq 1.7R \\ (2.6R-D)/(.9R) & 1.7R \leq D \leq 2.6R, \\ 0 & D \geq 2.6R \end{cases} \tag{6}$$

where R is the 3-dB pulse width (range cell dimension). Furthermore, the position of x_k is the sum of two random variables: one uniformly distributed between y_{i_1} and $y_{i_{N_k}}$, and the other Gaussian distributed with mean zero and variance σ^2. It is shown in the Appendix that the likelihood of the position of x_k can be approximated by

$$P_E(x_k) = (e^{-\varepsilon_k^2/2\sigma^2})/\mathrm{Max}(y_{i_{N_k}} - y_{i_1}, (2\pi\sigma^2)^{1/2}) , \tag{7}$$

where

$$\varepsilon_k = \mathrm{Max}\ (0, x_k - y_{i_{N_k}}, y_{i_1} - x_k) \tag{8}$$

is the distance from x_k to the nearest detection if x_k lies outside of the interval defined by the predicted positions; otherwise ε_k is zero. Finally, the number and position of false alarms in the range interval of interest R_I is given by the Poisson density

$$P_{FA}(N_{FA}) = \frac{(\lambda R_I)^{N_{FA}} e^{-\lambda R_I}}{(N_{FA})!\ (R_I)^{N_{FA}}}$$

$$= \frac{\lambda^{N_{FA}} e^{-\lambda R_I}}{(N_{FA})!} , \tag{9}$$

where λ is the false alarm density per unit length and the $(R_I)^{N_{FA}}$ factor in the denominator is due to the fact that the false alarms are uniformly distributed in range.

In terms of the previous expressions the likelihood of an N_T track combination is given by the following:

$$L(N_T) = P_{FA}(N_{FA}) \cdot$$

$$\binom{N_S N_T}{N_M} (P_D)^{N_S N_T - N_M} (1-P_D)^{N_M} \cdot$$

$$\left[\frac{1}{(2\pi\sigma^2)^{1/2}}\right]^{N_S N_T - N_M - N_{TR}} \prod_{i=1}^{N_T} \prod_{j=1}^{N_S} f(x_{ij} - y_{ij}) \cdot$$

$$\prod_{k=1}^{N_{DR}} P_R(x_k)\ P_e(x_k) \quad . \tag{10}$$

The first line represents the false alarm probability, the second line represents the detection probability, the third gives the measurement error prabability, and the last gives the resolution probability. The maximum likelihood method involves assigning to each i-th track (yielding predicted positions y_{ij}) a sequence of detections (x_{ij}) that maximize (10).

As presently formulated the maximum likelihood method would have trouble with the target geometry shown in Fig. 3. Let the n-tuple $(I_1, I_2, .., I_n)$ represent a track, where I_j is the detection associated with j-th scan of the track. In Fig. 3, there are two tracks, (1,1,1,1,1) and (2,2,2,2,M); M represents a miss, and detection #3 on scan #1 is a false alarm. However, the maximum likelihood method defined by (10) will yield the solution involving the three tracks (1,1,1,1,1), (2,2,2,2,M), and (3,2,1,M,M). The latter case is more likely (as defined by (10))for the following reasons: the false alarm likelihood has been increased by 6×10^4 (by eliminating the false alarm), the detection likelihood has been decreased by 0.6 (12 out of 15 detections instead of 9 out of 10 detections), the measurement likelihood is increased by removing a $(1/2\pi\sigma^2)^{1/2}$ factor (2 detections declared resolutions but one detection added) and by eliminating two Gaussian errors, and the resolution likelihood is decreased by $(1/2\pi\sigma^2)$. Thus, since 6×10^4 is greater than $(1/2\pi\sigma^2)^{1/2}$, the likelihood for three tracks is larger than the likelihood for two tracks. As formulated by (10), the maximum likelihood method will always try to eliminate false alarms by introducing false (extraneous) tracks.

To eliminate this problem, two factors have been introduced. One factor penalizes tracks that have unresolved detections and the second factor penalizes tracks that have missing detections. These factors are an attempt to compensate for the fact that the a priori probabilities of the number of tracks and separation of tracks is unknown. Thus, the modified likelihood is given by

$$L_M(N_T) = L(N_T)\,(F_R)^{N_{TR}-N_{DR}}(F_M)^{N_M} \quad . \tag{11}$$

Usually, we take $1 > F_M > F_R$. The values presently being used are $F_M = 0.2$ and $F_R = 0.1$. For the rest of this paper, the maximum likelihood method will be implemented by (11).

III. CALCULATION OF MAXIMUM LIKELIHOOD FUNCTIONS

Search techniques cannot be used to maximize the likelihood function (11) because of the large number of local maxima. To solve this computational problem the concept of a feasible track was introduced. Then the maximum likelihood of each combination of feasible tracks was evaluated.

In this study, 5 scans were considered and a feasible track required at least 3 detections. Furthermore, all detections in a feasible track were required to be within 2.6 range cells of the line joining the first and last detections. If two feasible tracks differ only by misses, for instance $(I_1, I_2, I_3, I_4, I_5)$ and (M, I_2, I_3, I_4, M), the track with additional misses is only retained if its velocity differs from the other track velocity by more than 30 ft/s where velocity is determined from the first and last detections.

Next the maximum likelihood is calculated for all single tracks. A direct search technique is used to determine the target's position on the first and last scan. For each detection associated with the track it is determined whether it is more advantageous to label the detection as coming from the track (with its associated Gaussian error) or whether to declare a false alarm and a missed detection*. At the end of this process, if a track has a detection for each scan, it is called a "perfect" track.

Next, the likelihood is calculated for each possible two-track combination. That is, if there are 30 feasible tracks, there are 30(29)/2 = 435 two-track combinations. If the two tracks do not have any common detections, the two tracks are said to be "isolated" and the maximum likelihoods for the single tracks are used. On the other hand, if the two tracks do have common detections, each track is considered to extend from its first to its last detection. For each detection associated with only one track, it is determined whether it is more advantageous to label the detection as coming from the track (with its associated Gaussian error) or whether to declare a false alarm and a missed detection. For detections common to both tracks, one of three actions is taken: 1) declare the tracks unresolved, 2) associate the detection with the nearest track and declare one target miss, or 3) declare two missed detections and a false alram. It should be noted that all of the previous calculations proceed on a scan-to scan basis Therefore, it is possible to obtain a slightly different likelihood if the scans were evaluated in a different order (e.g., if one introduced a miss on scan 2, one may not want (or be allowed) to introduce a miss on scan 3).

After all two-track combinations are evaluated, all three-track, four-track, etc., combinations are evaluated. Usually, if the true answer is an n-track combination, all n+1-track combinations are evaluated. Next, the best track combinations (usually the best 5 to 10 are saved) are maximized by the use of direct search techniques in which each target's position on the first and last scan is varied. Finally, the track combination with the maximum likelihood is chosen as the correct set of tracks.

When a large number of tracks is present, the computational time on NRL's ASC computer can become exorbitant. For instance, calculation of the likelihoods for a four-track combination of 45 feasible tracks requires 40 seconds. Thus, to increase computation speed the method was modified to take advantage of "perfect" tracks--those that have detections on each scan. Since it is very likely that the perfect track will be in all the high likelihood track combinations, only track combinations that include the perfect track (or tracks) will be evaluated. For instance, if there are 30 feasible tracks and tracks 2 and 8 are perfect tracks, only one two-track combination, 28 three-track combinations, and (28)(27)/2 four-track combinations will be evaluated. Thus, for this example only 407 (1 + 28 + 28(27)/2) track combinations need be evaluated instead of all the 31900 possible track combinations: (30(29)/2 + 30(29) (28)/6 + 30(29)(28)(27)/24).

IV. SIMULATION DESCRIPTION

Before the results of several simulations are given, the data generation technique will be described briefly. The targets are assumed to be travelling in a straight line at a constant speed. The radar detections are generated on a scan basis in the following manner: A decision is made on whether or not a target is detected. If a target is detected, its position is calculated according to the straight line, and a Gaussian wander is added to its position. Next, false alarms are generated according to a Poisson density, and all the detections are ordered in range. The detections are examined, and it is decided, whether adjacent detections should be merged. If a detection is not merged, a Gaussian measurement error is added. If several detections are merged, all merged detections are replaced by a single detection whose range is a Gaussian measurement error added to a detection uniformly distributed between the nearest and farthest merged detections.

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*A miss is never introduced if the miss lowers the number of detections below that required for a feasible track.

V. RESULTS

The pertinent simulation parameters are given in Table 1, and the target parameters are given in Table 2. The maximum likelihood approach was applied to 10 independent realizations of the 5 cases given in Table 2; and the results are summarized in Table 3. Of the 50 cases run, 7 were incorrectly identified.

TABLE 1 - SIMULATION PARAMETERS

PARAMETER	VALUE
Number of scans	5
Number of misses allowed in track	2
Probability of detection	0.85
Average number of false alarms per scan	0.3
Gaussian wander, standard deviation	100 ft
Gaussian measurement error, standard deviation	100 ft
Range interval	2.0 nmi
Range cell dimension	500 ft
Scan time	5.0 s
Penalty factor for resolution (F_R)	0.1
Penalty factor for misses (F_M)	0.2

TABLE 2 - TRACK PARAMETERS

CASE NO.	NO. OF TARGETS	INITIAL RANGES (nmi)	VELOCITIES (ft/s)
1R	1	U(98,100)*	G(1000,50)†
2	2	99.2 and 98.7	925 and 1000
3R	3	U(98, 100)*	G(1000, 50)†
3	3	99.1, 98.9, and 98.7	1000, 1000, and 1000
4	4	99.2, 98.7, [illegible].6, and 98.1	950, 900, 1000, and 900

* U(98,100) indicates that the initial target positions are uniformly distributed between the two ranges given

† G(1000,50) indicates that the velocities are Gaussian distributed; the first figure represents the mean value, and the second gives the standard deviation

TABLE 3 - SIMULATION RESULTS: NUMBER OF TIMES VARIOUS TRACK COMBINATIONS WERE SELECTED

CASE NO.	ONE TRACK		TWO TRACKS		THREE TRACKS		FOUR TRACKS	
	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect
1R	10							
2			10					
3R				3	6	1[a]		
3				1	9			
4						1	8	1[a]

[a] At least one track had a velocity error greater than 10%

However, it was judged (by the authors) that all 7 incorrect solutions were the most reasonable result. In most cases where the number of tracks was underestimated, the true track contained fewer than three detections and these were incorrectly assumed false alarms. The two cases where the track had a velocity error greater than 10% occurred because the track either used a false alarm or stole a detection from another track.

The ten examples of the four-track situation will be reviewed to illustrate the maximum likelihood method. The detections made on five scans on each repetition are shown in Figs. 4(a) through 4(j). In each figure the total range interval is 2 nmi. Note that for presentation purposes the ranges have been normalized by adding 5000 ft per scan, which corresponds to a velocity of 1000 ft/s. In the figures, dots represent detections, M's represent missed detections, arcs represent unresolved detections, FA indicates a false alarm, and the dashed lines represent the true tracks. In each scan the detections are numbered from right to left.

In Fig 4(a), the selection in accordance with the maximum likelihood is the following combination of four tracks: (1,1,M,M,1), (2,2,M,1,1), (3,M,M,2,2), and (4,3,2,3,3). The nearest false likelihood involving track (1,1,1,M,M) instead of (1,1,M,M,1) was only five times smaller.

In case 4(b), the three tracks (1,1,1,M,1), (2,2,2,1,2), and (3,M,3,2,3) were selected. Although incorrect, this obviously is what a reasonable person would select. The closest likelihood to this solution differs by a factor of 1000.

In case 4(c), the correct tracks (1,1,1,1,1), (M,2,2,2,M), (2,M,3,3,2), and (3,3,4,4,3) are chosen. All other track combinations considered are simple variations of the above tracks.

In case 4(d), the correct tracks (1,1,1,1,1), (M,2,2,2,M), (2,3,3,3,2), and (M,4,4,4,3) are selected. The closest likelihood, which is not a trival variation, differs by a factor of 10000.

In case 4(e), the correct track combination (1,1,1,1,1), (2,2,2,M,M), (2,3,3,2,2), and (M,4,4,3,3) had the largest likelihood. The largest likelihood of a three-track combination, ignoring track 2, differed by 1000.

In case 4(f), the track combination (1,1,1,1,1), (2,2,2,M,M), (M,3,3,2,2), and (3,4,4,3,M) was selected. All other combinations considered were simple variations of this case.

In case 4(g), the correct track combination (M,1,M,1,1), (M,2,1,M,1), (1,M,2,2,2), and (2,3,3,3,3) was selected even though there were only five detections on the first two tracks. The second largest likelihood, which dropped track 2, was 25 times smaller than the maximum likelihood.

In case 4(h), the four track combination (1,1,1,1,1), (M,2,2,2,2), (2,3,3,3,3), and (3,4,M,4,4) was selected. The second track selected two false alarms (detections 2) on scans 4 and 5 instead of detections 1. The likelihood of the true track combination differs from the maximum by a factor of five.

In case 4(i), the correct tracks (1,1,1,1,1), (2,2,2,M,M), (3,3,3,2,2), and (4,M,4,3,3) were selected. The likelihood of the three-track combination ignoring track 2 is 100000 times smaller.

In case 4(j), the correct tracks (1,1,1,M,M), (2,M,2,1,1), (M,2,3,M,2), and (3,3,4,2,3) are selected and the closest 3-track combination differs by a factor of 10000.

In summary, in the 10 repetitions, two false track combinations were selected. However, both of these false track combinations were very reasonable solutions. That is, with the given detections these are the tracks one would expect any operator or algorithm to deduce.

Since the maximum likelihood solution assumes that the probability of detection (P_d), probability of false alarm (P_{fa}), and Gaussian measurement error (σ) are all known a priori, a sensitivity analysis of the four-track combination was conducted. In the first case, the probability of detection was assumed to be 0.95 instead of the true value of 0.85; in the second case, the average number of false alarms per scan was assumed to be 0.6 instead of the true value of 0.3; in the third case, the Gaussian error was assumed to be 200 ft instead of the true value of 100 ft.; and in the last case, all the incorrect assumptions were made. The results are shown in Table 4. The three repetitions that produced different results were 1, 7, and 10. In case 1 (referring to Fig. 4(a)) when a larger Gaussian error was assumed, track (1,1,M,M,1) was replaced by track (1,1,1,M,M). This had the effect of removing a false alarm. In case 7, different tracks were produced when one assumed P_D = 0.95 and/or σ = 200 ft. The resulting three tracks (see Fig. 4(g)) are (M,2,1,M,1),(1,M,2,2,2), and (2,3,3,3,3); that is track (M,1,M,1,1) is no longer detected. In case 10 when all the incorrect assumptions were made, track (2,M,2,1,1) was dropped, resulting in only the three tracks (1,1,1,1,1), (2,2,3,M,2), and (3,3,4,2,3) being detected. In general, the maximum likelihood method is rather insensitive to the assumed parameters. The parameter that it is most sensitive to is the Gaussian error.

VI. RAID DETECTOR

In general the maximum likelihood method of initiating tracks works extremely well. However, since the method cannot be implemented because of the computational requirement, a modification of a raid detector studied by Flad [1977] is presently being investigated. The basic idea is to declare a target raid and estimate the raid velocity and number of targets in the raid.

A raid is initiated when M_1 uncorrelated detections on a previous scan correlate (associate) with the same M_2 detections on the present scan. (While one would prefer to initiate M_1M_2 tentative tracks, the computational time required grows exponentially). As shown in Fig. 5, raid tracking is performed by first calculating the raid velocity, which is determined by the centroid of the raid detections on each scan, and then using the raid velocity to predict new positions for each target detected on the present scan. Flad uses a fixed β filter for velocity, uses the present detections as the smoothed positions, and makes no attempt to estimate the number of targets in the raid.

We are presently changing the value of β on a scan-to-scan bases: using a higher value for β if the number of detections on the present and previous scans are the same. [illegible] number of targets in the raid is being estimated by two methods: maximum likelihood estimate and minim[illegible]n of a cost function. The maximum likelihood estimate consists of finding the values of N_T (the n[illegible]er of targets) and P_D

TABLE 4 - NUMBER OF TRACKS ESTIMATED FOR 4-TRACK CASE WHEN INCORRECT PARAMETERS ARE USED

REPETITION NO.	CORRECT ASSUMPTIONS	ASSUMED $P_D = 0.95$	ASSUMED NO. FA = 0.6	ASSUMED σ = 200 ft.	ALL INCORRECT ASSUMPTIONS
1	4	4	4	4*	4*
2	3	3	3	3	3
3	4	4	4	4	4
4	4	4	4	4	4
5	4	4	4	4	4
6	4	4	4	4	4
7	4	3	4	3	3
8	4*	4*	4*	4*	4*
9	4	4	4	4	4
10	4	4	4	4	3

* At least one track had a velocity error greater than 10λ.

(probability of detection) that maximize

$$L(N_T, P_D) = \prod_{j=1}^{N_S} \sum_{i=0}^{N_j} P_B(i)\ P_{FA}(N_j - i), \tag{12}$$

where $P_B(i)$ is the binomial detection probability of i detections of N_T targets

$$P_B(i) = \binom{N_T}{i} (P_D)^i\ (1-P_D)^{N_T - i}\ , \tag{13}$$

$P_{FA}(k)$ is the Poisson probability of k false alarms per scan

$$P_{FA}(k) = \lambda^k e^{-\lambda}/k!\ , \tag{14}$$

and N_j is the number of detections in the raid on each of the N_S scans. In this formulation, the false alarm density λ is assumed to have been estimated via environmental map monitoring. The second method minimizes the cost function

$$C(N_T, P_D) = (\mu - N_T P_D - \lambda)^2 + |\sigma_N^2 - N_T P_D (1-P_D) - \lambda| \tag{15}$$

where μ and σ_N^2 are the average and variance of the number of detections on each scan. For a given N_T, the value of P_D that minimizes (15) is

$$P_D = [2\mu - 2\lambda \pm 1]/[2N_T \pm 2] \tag{16}$$

where the appropriate sign depends on whether the term within the absolute value is plus or minus.

The two methods were compared by using 100 repetitions of a case where $N_S = 10$, $N_T = 3$, $P_D = 0.8$, and $\lambda = 0.3$. The results are summarized in Table 5.

TABLE 5 - COMPARISON OF METHODS FOR ESTIMATING NUMBER OF TARGETS IN A RAID

ESTIMATION METHOD	NUMBER OF TARGETS ESTIMATED				
	1	2	3	4	5
MAXIMUM LIKELIHOOD ESTIMATE	0	[illegible]	72	25	3
COST MINIMIZATION	0	11	76	10	3

Comparing the two methods, both methods yield similar results except for the fact that the maximum likelihood method tends to overestimate the number of targets. It should also be noted that the cost minimization is about 5 times quicker to calculate, since the maximum likelihood method requires a search to find the value of P_D that maximizes (12).

VII SUMMARY

The maximum likelihood method of initiating tracks works extremely well. However, the method cannot be implemented because of the enormous computational requirement. For instance, it took 40 seconds on the NRL's ASC computer to evaluate all possible 4-track combinations of 45 feasible tracks when none of the feasible tracks were "perfect". Thus, a more practical procedure must be considered. Presently, a modification of a raid detector studied by Flad (1977) is being investigated. The basic idea is to declare a target raid and estimate the raid velocity and number of targets in the raid.

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IX APPENDIX--LIKELIHOOD OF MERGED TARGETS

If several targets are merged, the position of the unresolved detection is given by

$$x = y + z, \tag{1}$$

where y is uniformly distributed between plus and minus A (the nearest and farthest predicted target positions of merged targets) and z is a Gaussian measurement error with mean 0 and variance σ^2. The density of x is given by the convolution,

$$p(x) = \int_{-A}^{A} \frac{1}{2A} \frac{1}{(2\pi\sigma^2)^{1/2}} e^{-(x-y)^2/2\sigma^2} dy \quad . \tag{2}$$

Equation (2) will now be evaluated for the two special cases when $A \gg \sigma$ and when $\sigma \gg A$. If $A \gg \sigma$ and $|x|<A$ (i.e., detection is between predicted positions), the integral of the Gaussian density is approximately 1, and (2) reduces to

$$p(x) = \frac{1}{2A} . \tag{3}$$

If $A \gg \sigma$ but $|x|>A$ (i.e., detection outside predicted positions), p(x) is approximately given by

$$P(x) = \frac{1}{2A} \quad \Phi(\frac{-\delta}{\sigma}) \tag{4}$$

where $|x| = A + \delta$

and

$$\Phi(T) = \int_{-\infty}^{T} \frac{1}{\sqrt{2\pi}} e^{-u^2/2} du \quad . \tag{5}$$

It should be noted that the situation $|x|> A$ will rarely occur when $A \gg \sigma$.

When $\sigma \gg A$ and $|x|< A$ (which will be very rare), the exponential is essentially one, and p(x) reduces to

$$p(x) = \frac{1}{(2\pi\sigma^2)^{1/2}} \tag{6}$$

On the other hand, when $\sigma \gg A$ and $|x|>A$, the exponential is a constant and can be pulled outside the integral resulting in

$$p(x) = \left(\frac{1}{2\pi\sigma^2}\right)^{1/2} e^{-\delta^2/2\sigma^2} , \tag{7}$$

where $|x| = A + \delta$. Combining (3) through (7), p(x) can be approximated by

$$p(x) = \frac{e^{-\delta^2/2\sigma^2}}{\mathrm{Max}\{2A, (2\pi\sigma^2)^{1/2}\}} \tag{8}$$

where $\delta = \mathrm{Max}\ \{0, x-A, -A-x\}$.

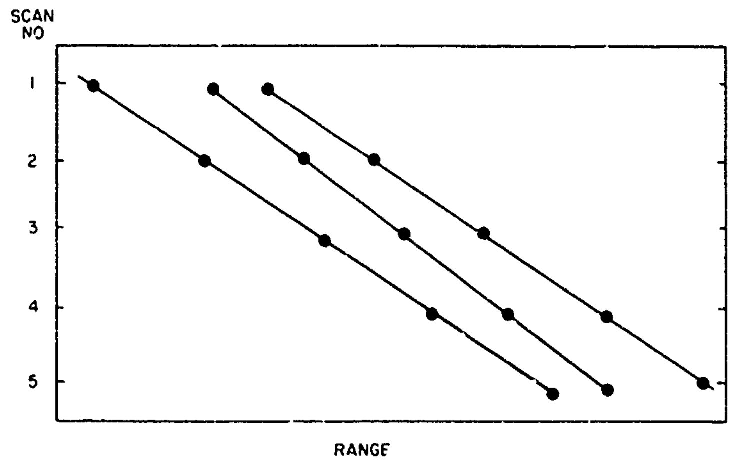

Fig. 1 History of five scans of three tracks showing all detections present.

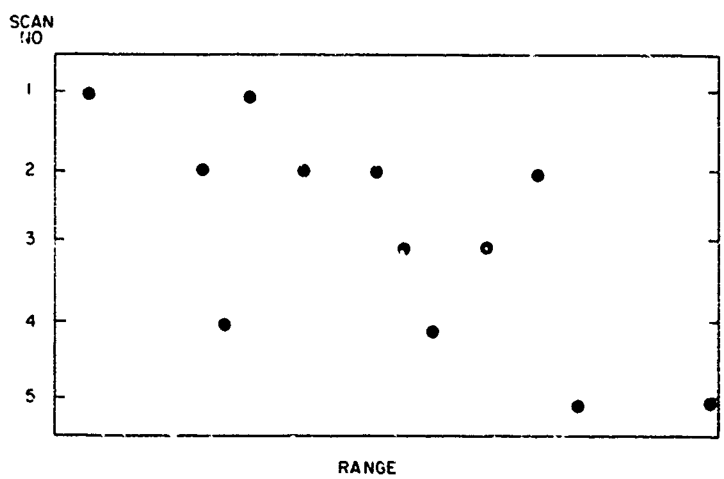

Fig. 2 History of five scans in which detections were missed, detections were merged, and false alarms occurred.

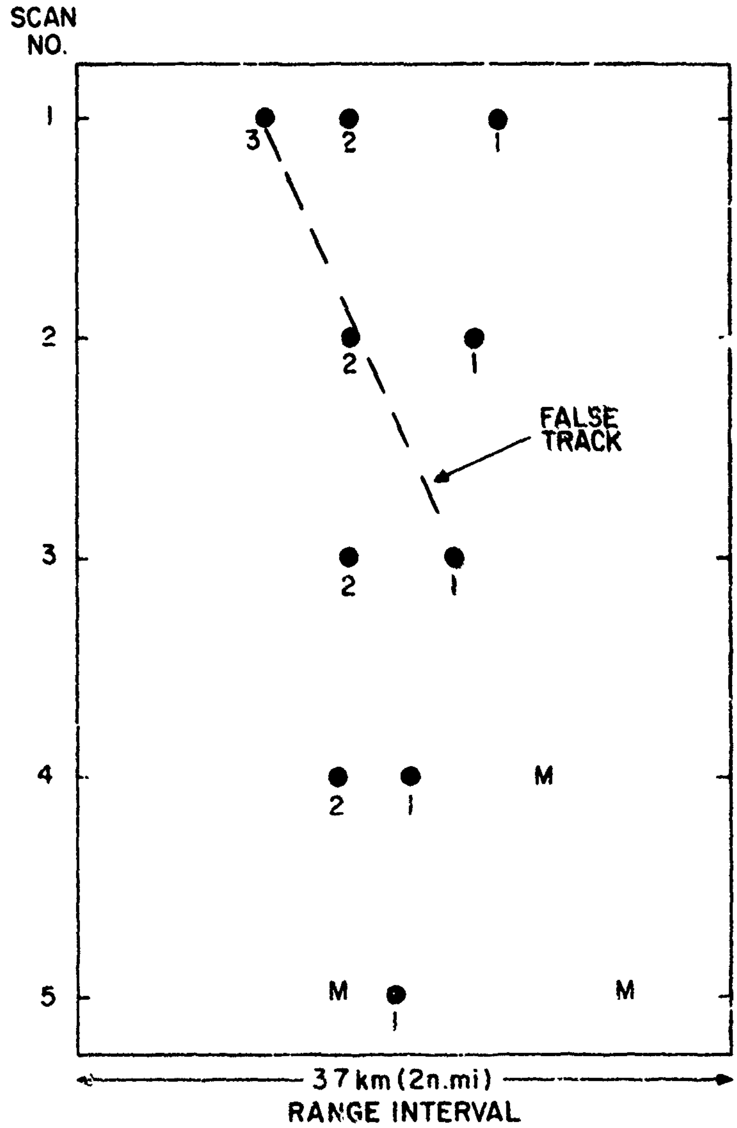

Fig. 3 Scan history showing a false crack created as the result of a false alarm and the incorporation of detections of actual tracks.

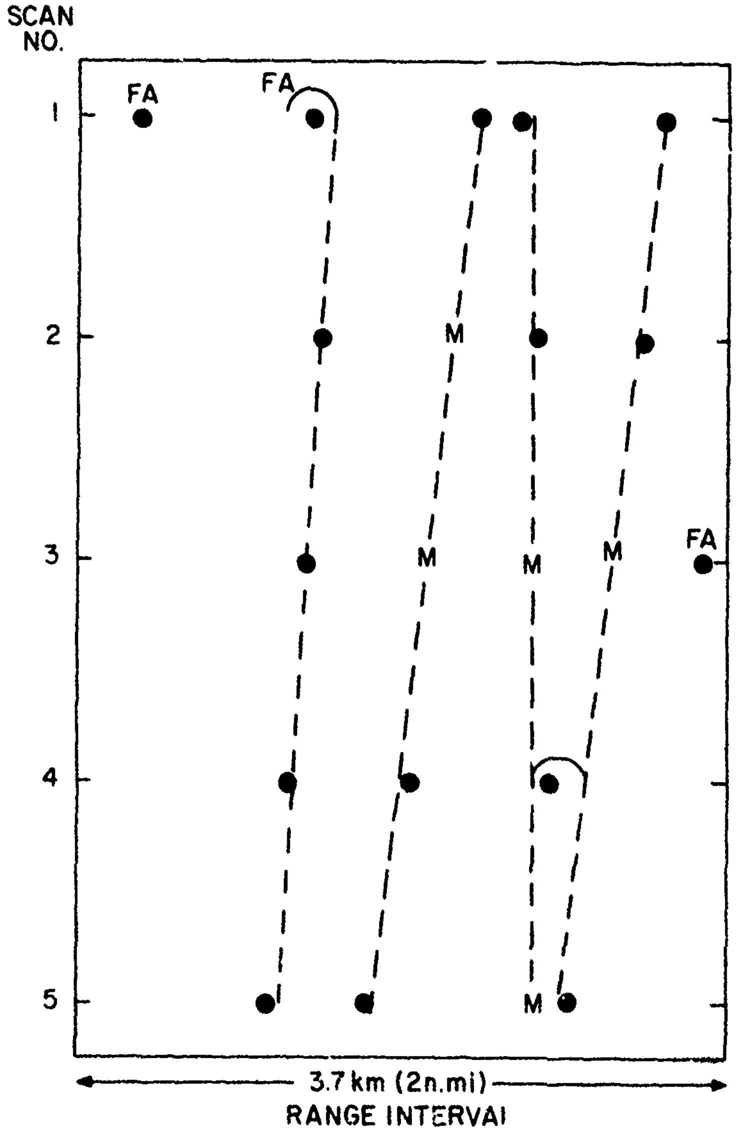

Figure 4(a)

Fig. 4 The diagrams (a) through (j) making up this figure present 10 iterations of one simulated 4-target raid and the radar detections that occurred. The variations in results are caused by random false alarms that were introduced and by noise and clutter. Dots represent detections, M's represent missed detections, arcs represent unresolved detections, and FA indicates a false alarm. The dashed lines show the true tracks. In each scan the detections are numbered from right to left.

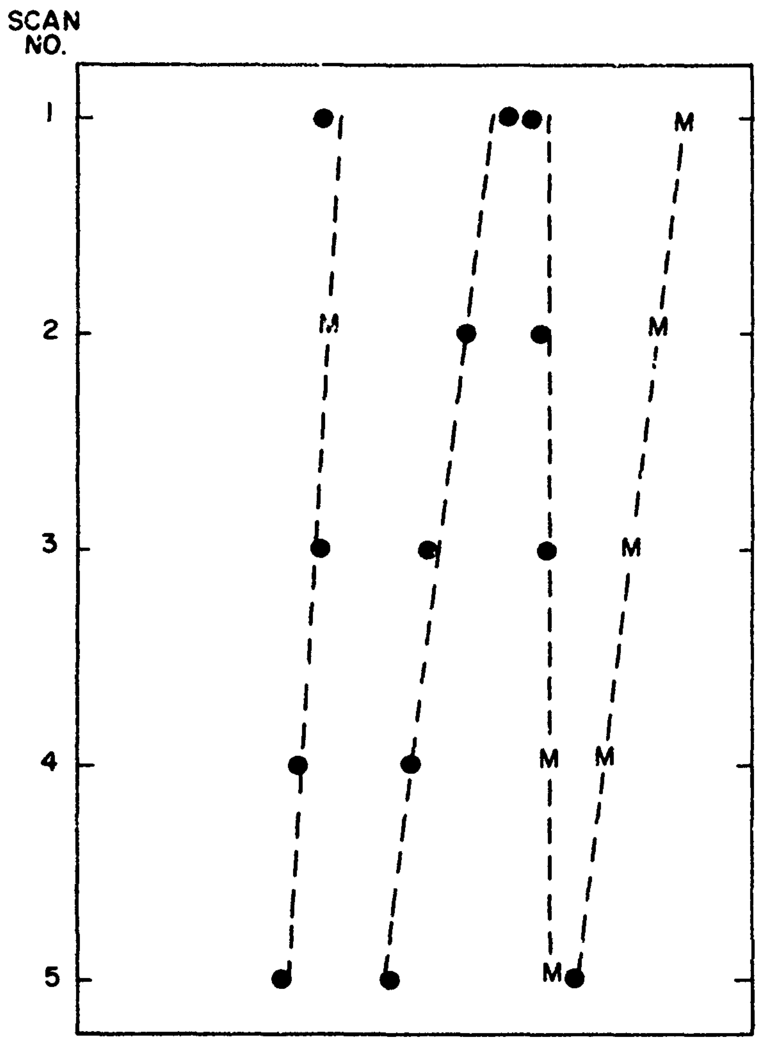

Figure 4(b)

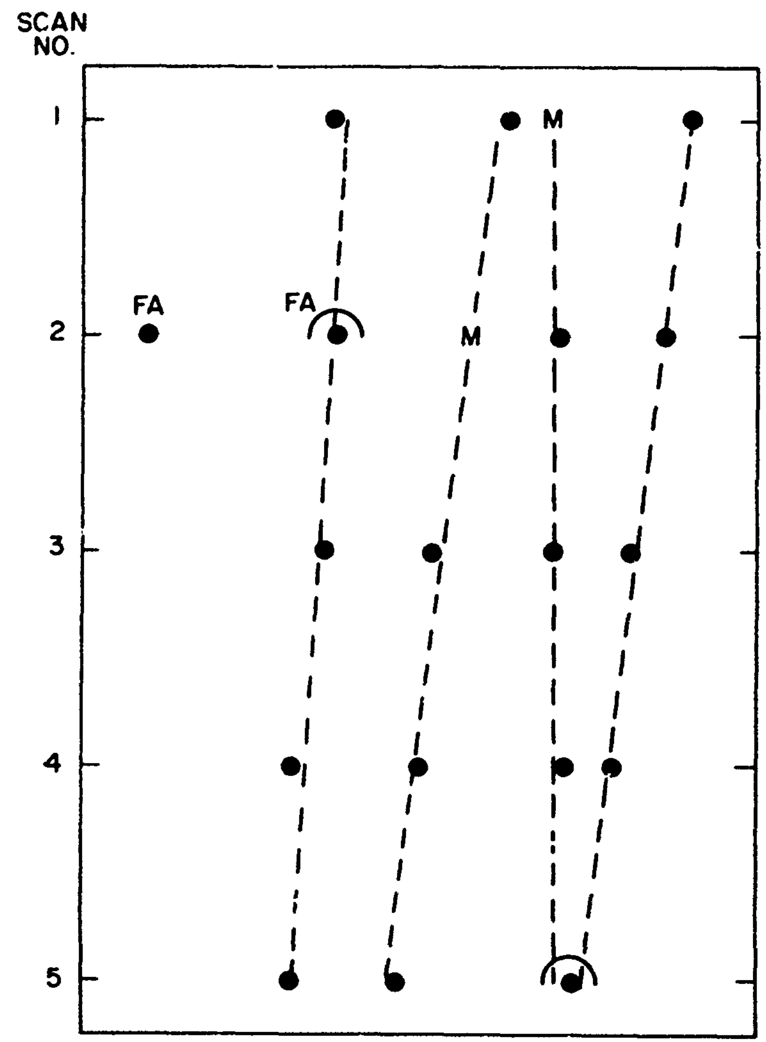

Figure 4(c)

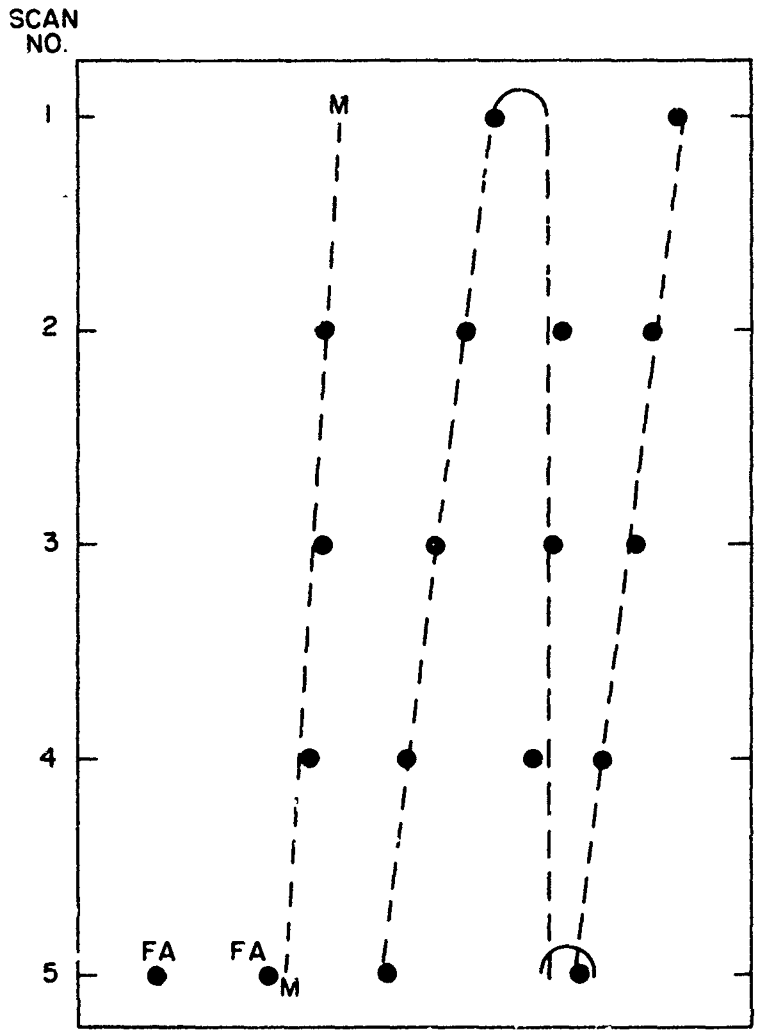

Figure 4(d)

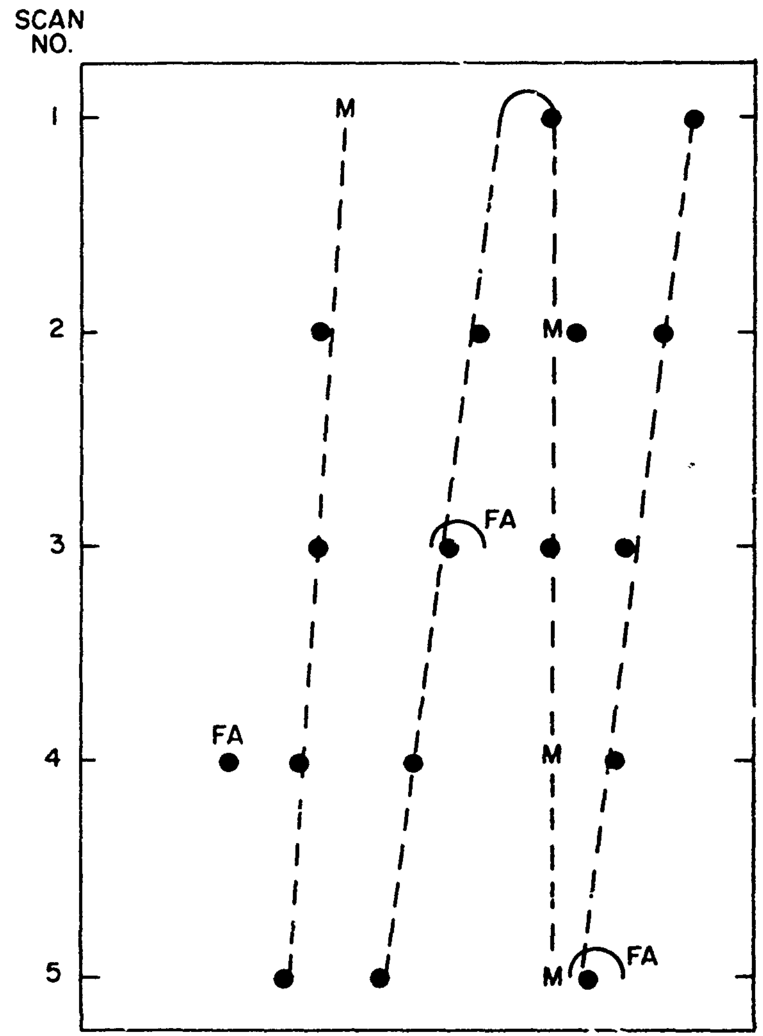

Figure 4(e)

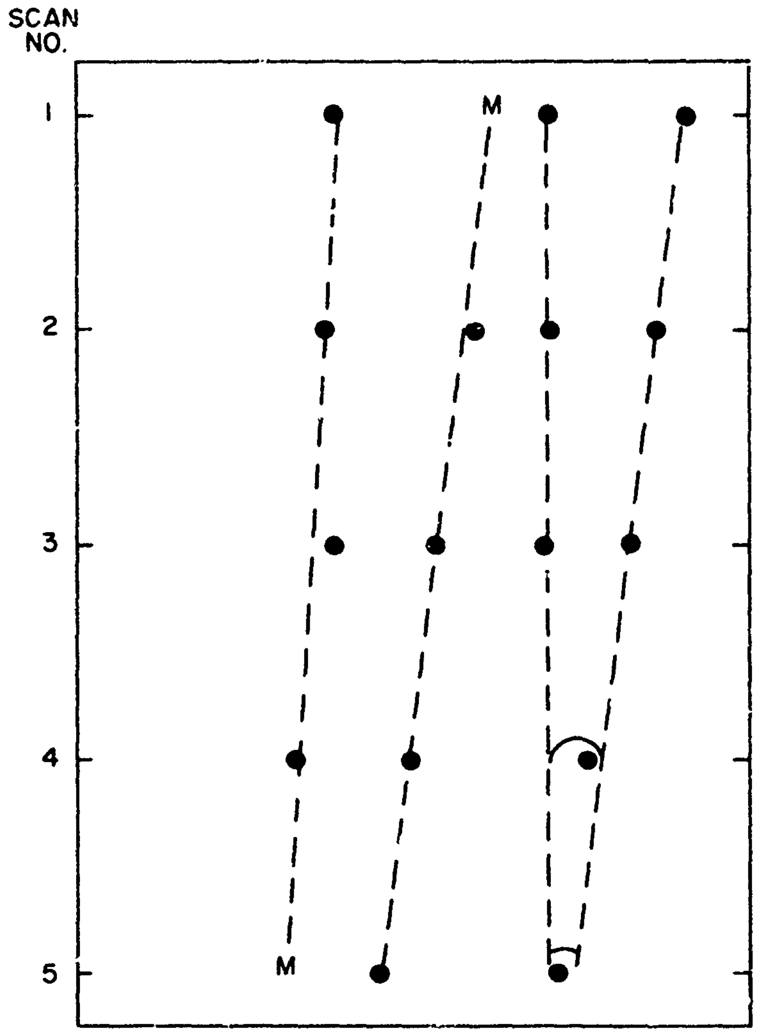

Figure 4(f)

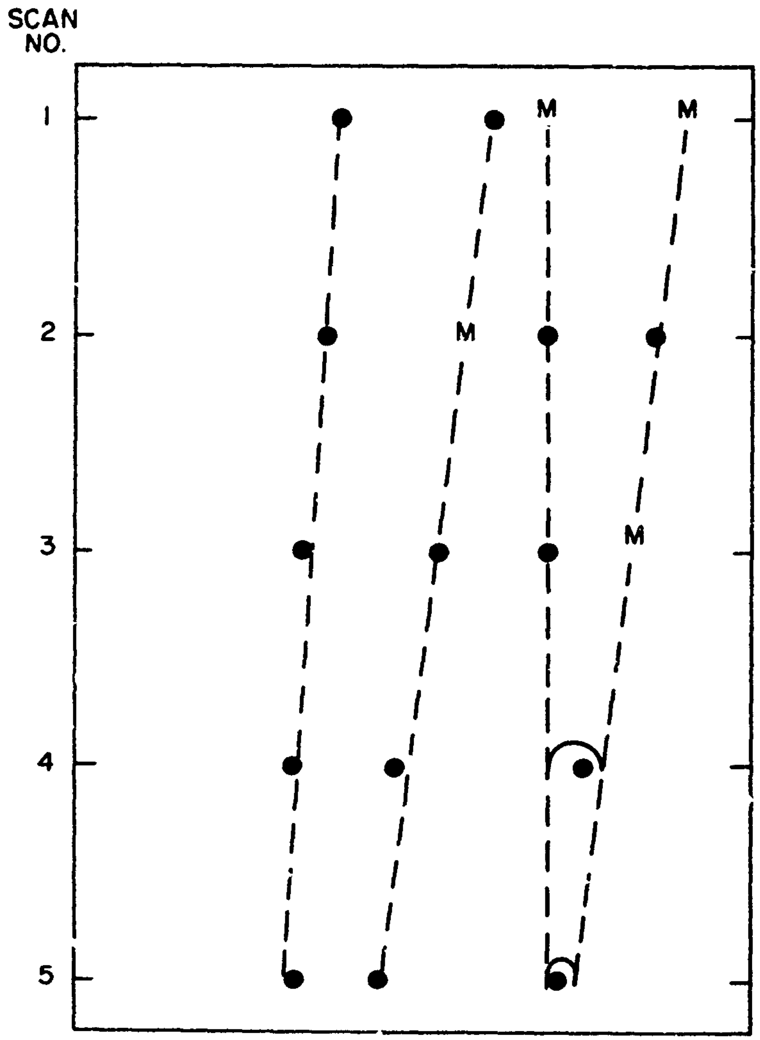

Figure 4(g)

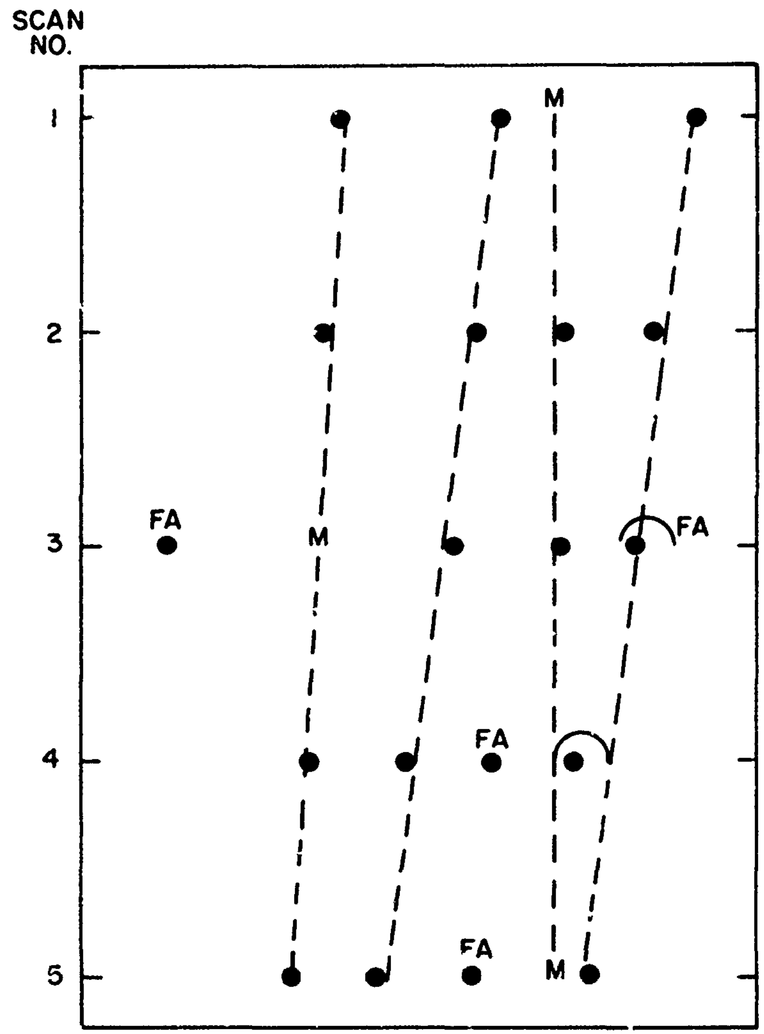

Figure 4(h)

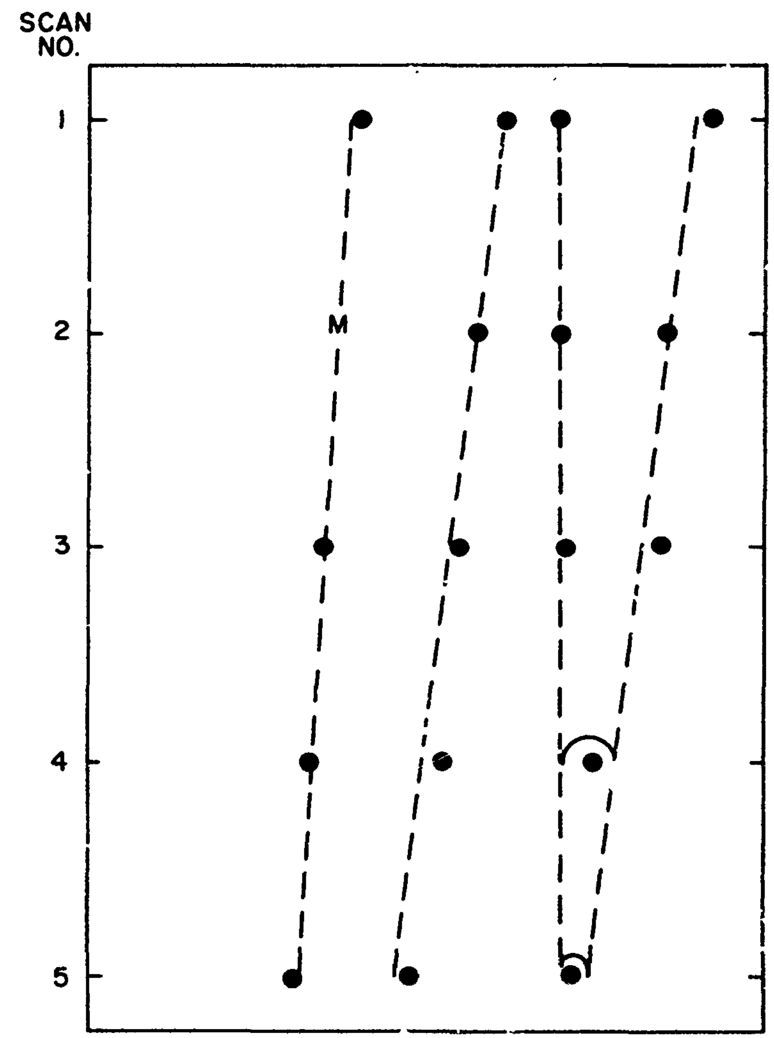

Figure 4(i)

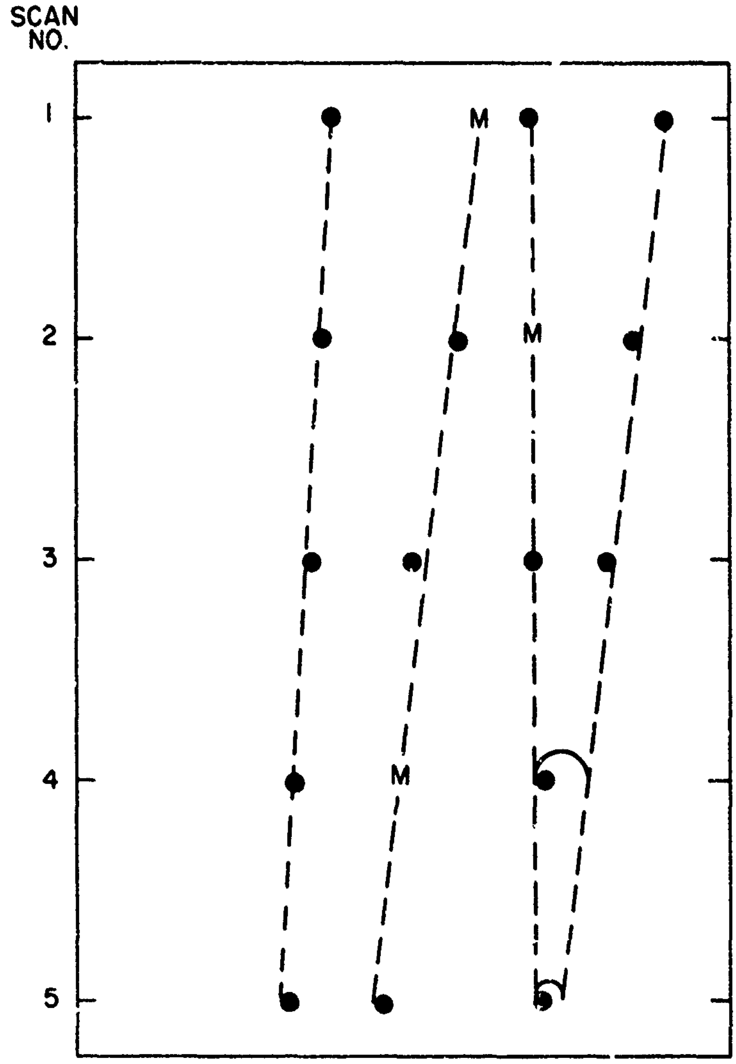

Figure 4(j)

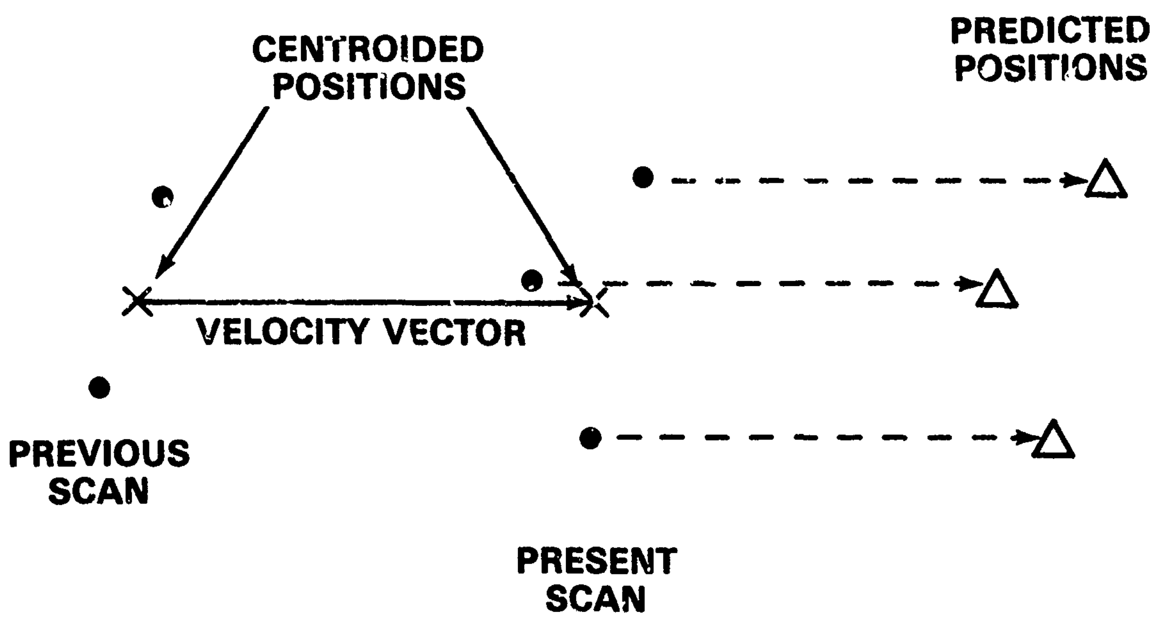

Fig. 5 Raid tracking geometry

DISCUSSION

H.B.Driessen, Netherlands

What is the criterion to decide if the track was correct or incorrect (Table 3)?

Author's Reply

A track is incorrect if either there are the wrong number of tracks or a track has a velocity error greater than 10%. (See footnote on Table 3.)

G.Binias, FRG

Have you determined the probability of losing tracks by using the raid tracker's velocity (acceleration) estimation instead of estimating values for individual targets?

Author's Reply

No. However, since the raid tracker should only be used in a dense detection environment (where individual tracks will have either missed or false correlations) we would expect the raid tracker to have better performance.

D.B.Reid, USA

How does your work compare to Morefield?

Author's Reply

Morefield does not consider the probability of resolution in his formulation. We have tried to use his integer programming method, although it cannot be applied directly since the probability coefficients will change if there are unresolved detections. However, we are presently trying to modify his method.

AUTOMATIC RADAR TRACKING IN TERMINAL AIR TRAFFIC CONTROL FACILITIES

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Washington, D. C., U.S.A.

ABSTRACT

The 62 busiest air traffic control terminal facilities in the United States have been equipped with a computer-aided radar detection system which has been called ARTS III. The acronym is derived from Automatic Radar Terminal System. This system was deployed in the field during 1971 and 1972. The ARTS III has been held up as an example of a successful program since it was done on schedule and within budget and was very well received by the operational work force.

Although the system is highly reliable, it is totally simplex and is very basic. Only transponder-equipped aircraft are tracked within the basic ARTS III. The main failure mode of the system is the use of analog video which would still be available in the event of a digitizer or computer malfunction. One of the main reasons which dictated beacon-only tracking was the difficulty in developing a digitizer to handle primary radar in the terminal environment. Site characteristics, antenna rotational rate, and pulse repetition frequency of terminal air traffic control radars resulted in a high sampling rate not only of desired targets but of ground and weather clutter.

The FAA, together with Sperry UNIVAC, has developed a radar tracking system for use in the terminal area. The extractor is referred to as a Sensor Receiver and Processor (SRAP). It detects both primary radar and secondary radar targets and correlates the two for transmission to the central computer. The primary radar extractor portion of the SRAP employs a rank order quantizer as the first detector so that quantizing of signals is done on a non-parametric basis. The device also employs a dynamic correlation measurement technique to produce a tight clutter false alarm control. The ARTS III computer program has been modified to accept data already azimuthally correlated between primary and secondary signals.

INTRODUCTION

Thirty-five years ago we were in the middle of World War II and the early applications of radar to the problem of air defense were being followed. It had also become apparent by that time that radar could also be used for the guidance and safe landing of friendly aircraft. Ever since that time developments related to radar were influenced by both of these applications.

Twenty years ago the state of the art relative to real time command and control was the SAGE system. This was the Semi-Automatic Ground Environment developed for North American Air Defense. It was obvious to many, especially from the military, that this system could also satisfy all the requirements of the FAA for air traffic control surveillance. A close investigation of the SAGE system, however, led the FAA to the conclusion that additional developments were necessary to produce a system which could satisfy the specific requirements for air traffic control although it was granted that the requirement of providing surveillance of an aircraft was common between the air defense and the air traffic control mission.

During the 60s the FAA initiated the development of NAS En Route Stage A. This system has now been deployed at all 20 of the air route traffic control centers in the 48 coterminous states and provides an automatic radar detection and processing capability on both primary and secondary radar. The same digitizers were proposed for use in a terminal air traffic control environment but this was discarded in the late 60s because of a number of constraints imposed by the more severe terminal environment. Among these factors are the greater maneuvering aspect from aircraft in the terminal area, the fact that aircraft are, generally speaking, closer together, the requirement that the environment be scanned at a higher rate, the higher pulse repetition frequency resulting from the increased antenna rotational speed, and the fact that there are less prerogatives available with respect to siting criteria since the radar antenna usually must be sited on the airport. As a consequence of these difficulties in digitizing primary radar for use in the terminal, it was decided to implement automation in a manner whereby only secondary radar was digitized and utilized by the computer. The ARTS III system was developed and deployed on that basis and is now operating in the 60 busiest terminal areas in the United States. This system was well received in the field and has been very successful.

Even before the basic ARTS III systems were deployed the FAA launched an ARTS III Enhancement program. Some of the products of this enhancement program have already been deployed. One of these is the Minimum Safe Altitude Warning (MSAW) program. This program compares the altitude being transmitted from a transponder and compares this with a computer stored map of safe altitudes and desired heights along the approach course. When the computer determines that the projected course will result in an unsafe altitude condition, an audio and visual alert is provided to the controller. Another product of the enhancement program which has been deployed is the Conflict Alert program which compares trajectories of all aircraft pairs within the surveillance capability of the system and provides alerts to the controller when a potential conflict is found to be imminent. The main thrust of the enhancement activity, however, has been related to system reliability, system capacity and the addition of primary radar capability. Although the ARTS III system has demonstrated good reliability the system is simplex and no redundancy has been provided for either the computer or the secondary radar digitizer. Since the digitizer data has been superimposed on an analog display the most obvious failure mode is one where the total analog picture is still available.

Since it is apparent that every additional functional capability which gets added to a system such as ARTS III results in additional data being presented on the controller's display, it is believed necessary that the problem of display clutter must be solved. The most obvious direction is to move toward a full digital ARTS system. The elimination of the analog data could tidy up the display to the point where additional data could be provided in such a manner as to be easily ingested by the controller. It is obvious that a required condition necessary for the removal of the broad band data is a significantly increased system reliability. To this end the ARTS III computer has been modified to provide a multi-

processing capability. The computer program executive has been redesigned to make use of this multi-processing capability and operate in a fail safe/fail soft manner.

The basic ARTS III system provides beacon-only tracking. The tracker has been optimized with respect to the probability of correlation of a track and a datum point on a scan basis. Some measurements have shown this probability to be in the order of 85 percent. A study has shown (Birkholz, Heidbrink, Wold, October 1972) that the addition of primary radar to help in the correlation process would improve the probability of correlation to something in the order of 99 percent. This would indicate that in the high density terminal environment even with a high incidence of transponder equipped aircraft, the improved tracking reliability provided by the addition of digitized primary radar is justified. At the lower density facilities, it is obvious that the addition of digitized primary would allow for the tracking of non-transponder equipped aircraft. This improvement to the ARTS III which includes the fail safe/fail soft executive, the fail safe/fail soft program and the addition of primary radar tracking is referred to as the ARTS IIIA system and is presently being deployed.

With a view toward the eventual full digital ARTS system, the FAA's Research and Development Service has deployed a system in the Tampa, Fla. area to demonstrate the feasibility of all digital operations using the ARTS IIIA system as a base. An ASR-6 radar at Sarasota, Fla. has been digitized and digitally remoted to the control facility at Tampa some 35 miles away. The device that provides the digitizing is the Sensor Receiver and Processor (SRAP) designed by the Defense Systems Division of Sperry UNIVAC (Freeberg, Joyce, Kemp and Saltsman, December 1975). The main thrust of this paper will be to describe the operation of the SRAP. In addition to providing digital-only data to the Tampa controllers based on the Sarasota radar, digital surveillance data from both the Tampa and Sarasota radars are transmitted in narrow band fashion to four satellite towers and the information is presented on a Tower Cab Digital Display designed by Magnavox.

SENSOR RECEIVER AND PROCESSOR (SRAP)

It is probably true that a description of a radar digitizer or plot extractor starts out by saying the intent is to provide the maximum probability of detecting targets and at the same time providing a minimum false alarm rate. Trite as this might be, this is certainly the intent of the radar process subsystem for FAA's terminal air traffic control. The basic system consideration is the number of detection levels or filters,designed so that interference is discriminated against as early in the processing chain as possible, to limit the amount of processing required, and in addition, to optimize the relationship between target detection and false targets. The first detector can be thought of as being on a microsecond to microsecond basis. Its main function is to determine along a sweep radial indications of a signal as distinguished from receiver noise. The second detector is the device where signals which have been quantized are correlated in azimuth to produce target reports. Figure 1 is a block diagram of the SRAP. This paper concentrates on a description of the operation of the primary radar processing and, therefore, is concerned with the two boxes on top: the Radar Extractor (REX) and the Radar Microcontroller (RMC). The boxes below handle secondary radar and the CPS correlates radar targets with beacon targets.

Radar Extractor (REX)

The range of the radar is broken down into range cells in the order of a pulse length which is the basic resolution capability of the system. One way to discriminate between signal and noise is on the basis of a priori knowledge of the signal and noise characteristics. A discriminator designed on this basis would be called a parametric detector. The properties of radar signals and noise are such, however, that much of their behavior is not predictable and a discriminator which is non-parametric is desirable. Among the non-parametric devices considered there are devices such as the multi-level quantizer and the rank sum quantizer but the one chosen for the SRAP is the rank order quantizer.

Video signals from the radar receiver are presented to the SRAP input. A range clock synchronized with the radar triggers provides for the sampling of the radar video every sixteenth of a mile in range corresponding to a sample time of 722 manoseconds. This compares with a pulsewidth of 833 manoseconds for the ASR-4, 5 and 6 systems. The video amplitude in each range cell is quantized by a ten-bit analog-to-digital converter commensurate with a 60 db dynamic range. Since it is necessary to quantize both MTI and NORMAL video the converter is time-multiplexed between the two videos and a ten-bit sample of each is produced for each range cell (See Figure 2).

Since the ASR-7 and ASR-8 can provide digital video, the option is available to accept ten-bit video samples, to compensate for operation in frequency diversity and provide time-multiplexed ten-bit samples of normal and MTI signals each range cell interval. The alternative for these radars is to use the digital-to-analog converters in the radar receivers to provide synthetic analog to the analog-to-digital converters in the SRAP. The main problem with this alternative is that in the digital-to-analog-to-digital conversion some bits are lost which compromises the operation of the Rank Order Quantizer.

The Rank Order Quantizer (ROQ) consists of a shift register which is 27 range cells long by ten bits wide (Figure 3). At a given time the ten bits in the center of the register represent the amplitude for the range cell to be quantized. The surrounding locations hold the values for the 13 range cells preceding and the 13 range cells following. The two range cells immediately surrounding the candidate cell form a guard band and are not considered in the comparison operation. The contents of the center cell are compared with the contents of the other 24 cells. For half of the comparisons the value of the center cell must be greater than the other cell to score a one while for the other half a greater or equal comparison will score a one. The score for these 24 comparisons is then totaled yielding a count between 0 and 24. Since both NORMAL and MTI signals must be quantized, the actual shift register has 53 range cell positions and is clocked at half range-cell increments. The output is a five-bit rank twice per range cell - one for NORMAL and one for MTI. The ROQ is a distribution-free detector and so it produces a constant bit rate which can be predicted on the basis of the threshold settings essentially independent of the statistical variations in the amplitude of the video. For example, at a threshold setting of 24 the probability of quantizing on noise would be 1/25 or 4%. At a setting of 23 the resulting probability is 8%.

Hit Processing

Referring to Figure 4, the next obvious operation is the use of the rank numbers to determine "hits" for the purpose of target declaration. For each range cell the rank number is compared to a threshold provided by parameters stored in the radar microcontroller (RMC). If the rank is greater than or equal to the threshold a "1" is generated for that range cell. This results in two serial bit streams, one for NORMAL - one for MTI, with each serial bit representing the presence or absence of a hit in a particular range cell. Selection between the NORMAL and MTI serial bit stream for target detecti n is based on feedback from the clutter map generated in the RMC.

In addition to processing hits f.r the purpose of target declaration, it is also necessary to estimate the clutter situation for purposes of threshold setting, video selection and weather detection. The first step in this process is to produce clutter "hits" analogous to the target "hits described above. The only differences in the process are that a separate threshold from the RMC is utilized and there is no selection between NORMAL and MTI so that a full range of clutter hits is provided for both.

Target Declaration

A range-oriented memory consisting of a 27-bit word for each range cell is the basis for the target detection logic. On the basis of the clutter map generated in the RMC bits from either the NORMAL or MTI serial stream are presented to the range-ordered memory. The following information is accumulated and stored utilizing 23 of the 27 available bits:

MC Miss Count, number of successive misses after last hit

HC Hit Count, number of hits since start of the record

SC Sweep Count, number of sweeps since the first hit

SW Sweep Moment, accumulated sum of sweep counts associated with hits

Target end is indicated by the Miss Count (MC) reaching a Miss Count Threshold (MTC) provided by the RMC. When this occurs the hit count is examined to see if it has reached a Hit Count Threshold (HTC) also provided by the RMC. If so, the record is sent to the REX FIFO buffer for processing by the RMC. Otherwise, the record is discarded.

Clutter Monitor

It has been shown (Lefferts, Robert E., May 1976) that for the purpose of discriminating against clutter and for detecting weather returns a real time estimate of the clutter azimuth correlation factor is more significant than a measure of total energy returned. The method chosen for estimating the correlation factor is the counting of "isolated hits". An "isolated hit" is defined as an output of the ROQ meeting or exceeding a threshold for a particular range cell while being less than the threshold on both preceding and succeeding pulse periods. Clutter monitor words each consisting of four fields hold the sum of the isolated hits for NORMAL and MTI over two range increments of 32 range cells. These words are stored in the REX FIFO buffer for processing by the RMC.

Radar Microcontroller

The Radar Microcontroller (RMC) is a general purpose microprocessor which operates at a basic speed of 200 manoseconds per instruction. Information furnished from the REX is stored in the First In/First Out (FIFO) buffer. The basic outputs from the REX which are utilized by the RMC are primitive target reports from the target processing logic and isolated hit counts from the clutter monitor logic, The main functions of the RMC are the following: 1) Determination of target range azimuth and quality; 2) Filtering of targets on the basis of quality and formatting for output; 3) The scan to scan to scan integration of the normal isolated hit counts and generation of a clutter map for NORMAL/MTI selection; 4) Computing of areas of light and heavy weather and formatting for output.

Clutter Monitor Word Processing

For the purpose of processing normal isolated hits, the coverage area of the radar is broken down into zones which are 32 range cells by 32 azimuth change pulses. With a 64-mile range this provides 4096 clutter zones in one scan of the antenna. Clutter monitor words received from the FIFO contain '-bit representations of the numbers of isolated hits over 32 range cell increments of the sweep range for both NORMAL and MTI clutter hits. For each zone the number of normal isolated hits is accumulated in the Normal Video Isolated Hits Sector Summary. These accumulated sums of the normal isolated hits in a sector are integrated over a number of scans to produce a clutter map. This map is utilized as feedback to the REX for the selection of either NORMAL or MTI target hits for the target hit processing logic. In each sector the accumulated value of normal isolated hit count is compared against two thresholds: one for light weather and one for heavy weather. The result of this comparison is the computation of a weather map which is formatted for output.

The MTI isolated hits are processed in a sliding window which consists of a wedge 32 azimuth changes pulses in azimuty. During each sweep the current isolated hit count is added into the sliding window and the value which is 32 sweeps old is subtracted. This dynamic integrated value of MTI isolated hits is utilized for second threshold processing of targets within the radar microcontroller.

Target Processing

The first task performed in target processing is to compare records from the REX for the purpose of determining if there are any records in adjacent range cells or at adjacent azimuths. The target range and azimuth are then computed in a straightforward fashion giving appropriate weighting to adjacent records.

Once the range and azimuth have been determined, a determination is made as to whether NORMAL or MTI was selected for that zone. In the case of MTI selection, a second threshold test is applied to the record hit count. A threshold is computed on the basis of the isolated hits accumulated in the MTI sliding window. Any reports which fall below this threshold are discarded. Target reports whose range and azimuth have been determined to fall in zones where normal video has been selected are not subjected to second threshold processing. A report quality field of three bits is associated with each target report. Basically this identifier is a measure of how much the hit count exceeds a specified threshold. Maximum value for quality is 7 and any hit count which exceeds this value is tagged with the value 7.

SUMMARY

The SRAP has proven to be a successful development for the addition of primary radar tracking to the ARTS III systems. The Rank Order Quantizer provides a constant probability of quantizing on noise essentially independent of the statistical variation of amplitude of the video input. The technique of counting "isolated hits" was found to be a good method of providing an on-line estimate of the self-correlation property of the environment. The use of this measure of the correlation as the basis for selecting MTI or NORMAL and for the determination of weather thresholds has been effective.

With regard to reducing the declaration of targets due to clutter, it has been found that the us[illegible]he isolated MTI hit count to threshold the minimum hit count for target declaration in areas where M[illegible]s selected is effective in controlling the false alarm rate. In addition, the use of target quality to control the data load allows effective tracking of all targets.

References

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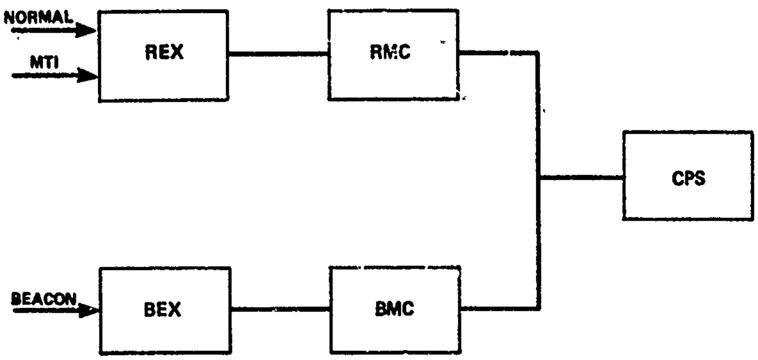

Fig.1 SRAP block diagram

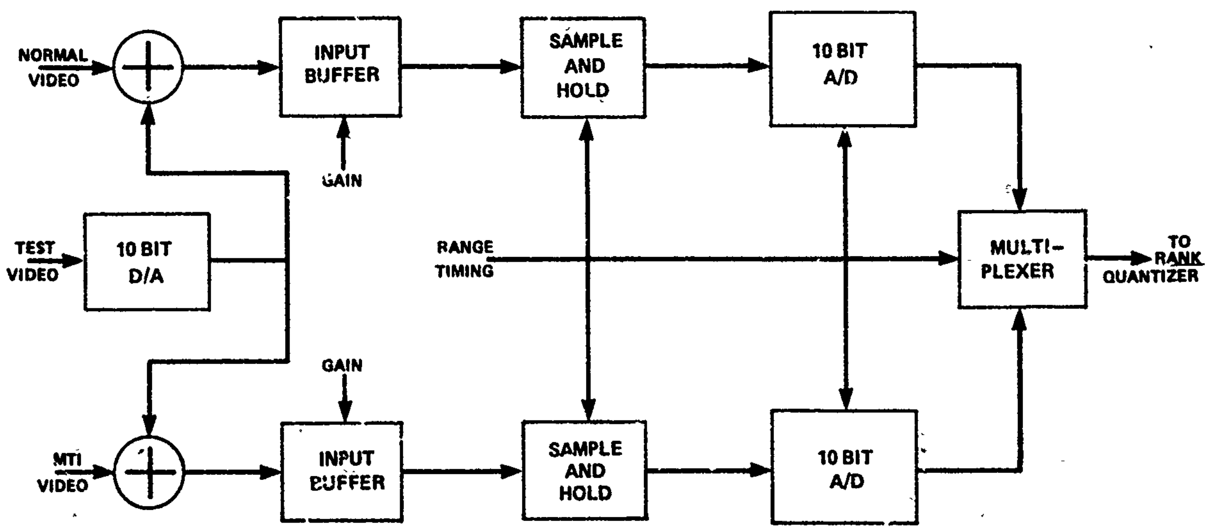

Fig.2 MTI/NORMAL A/D multiplexer

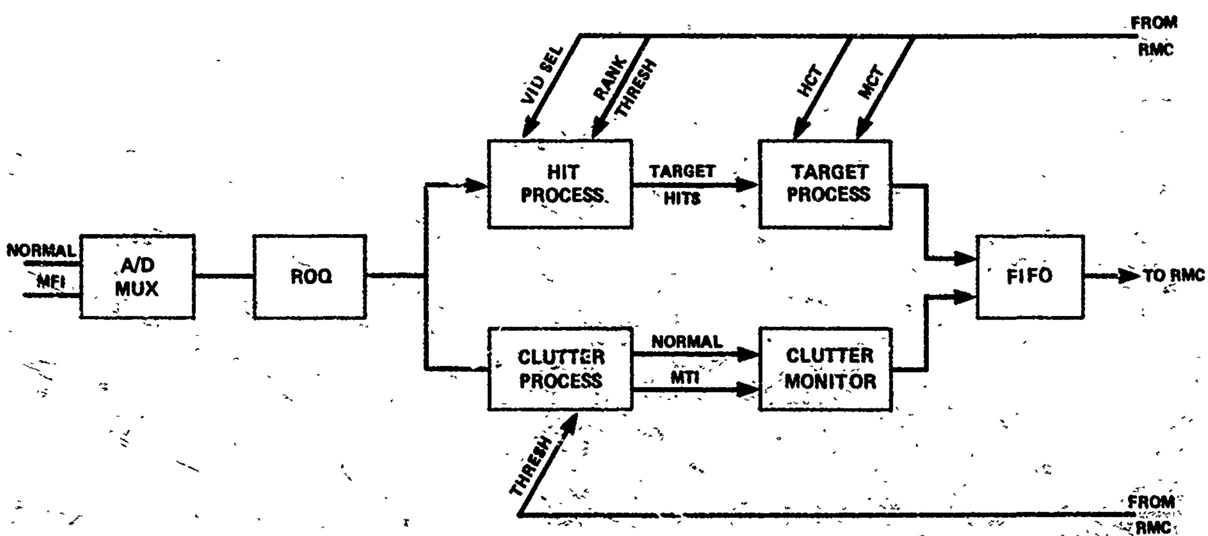

Fig.3 ROQ logic

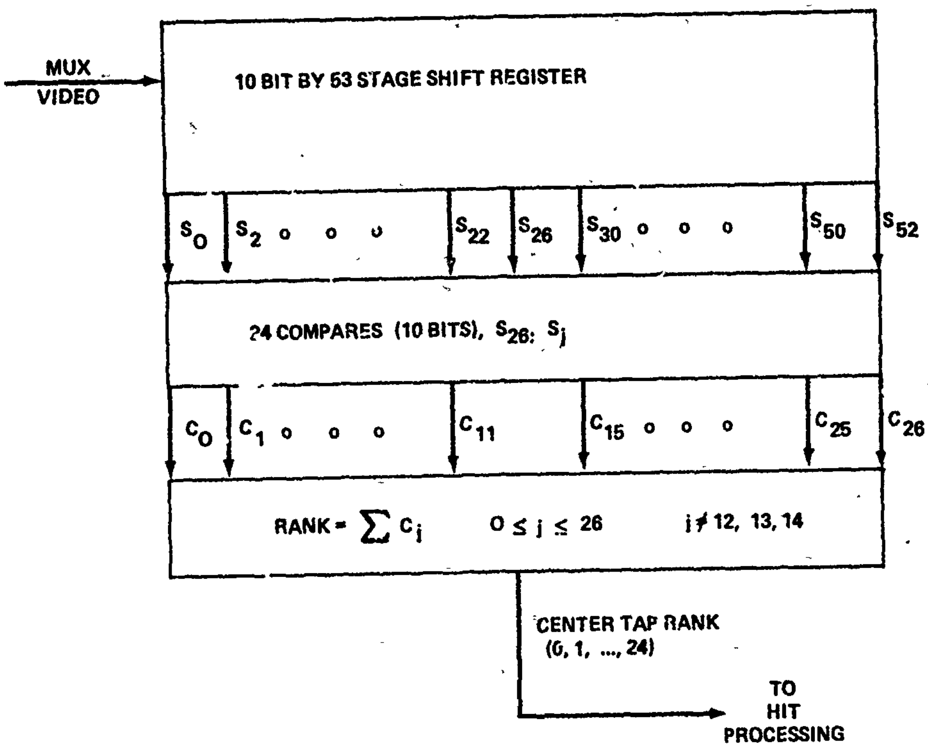

Fig.4 Radar extractor (REX)

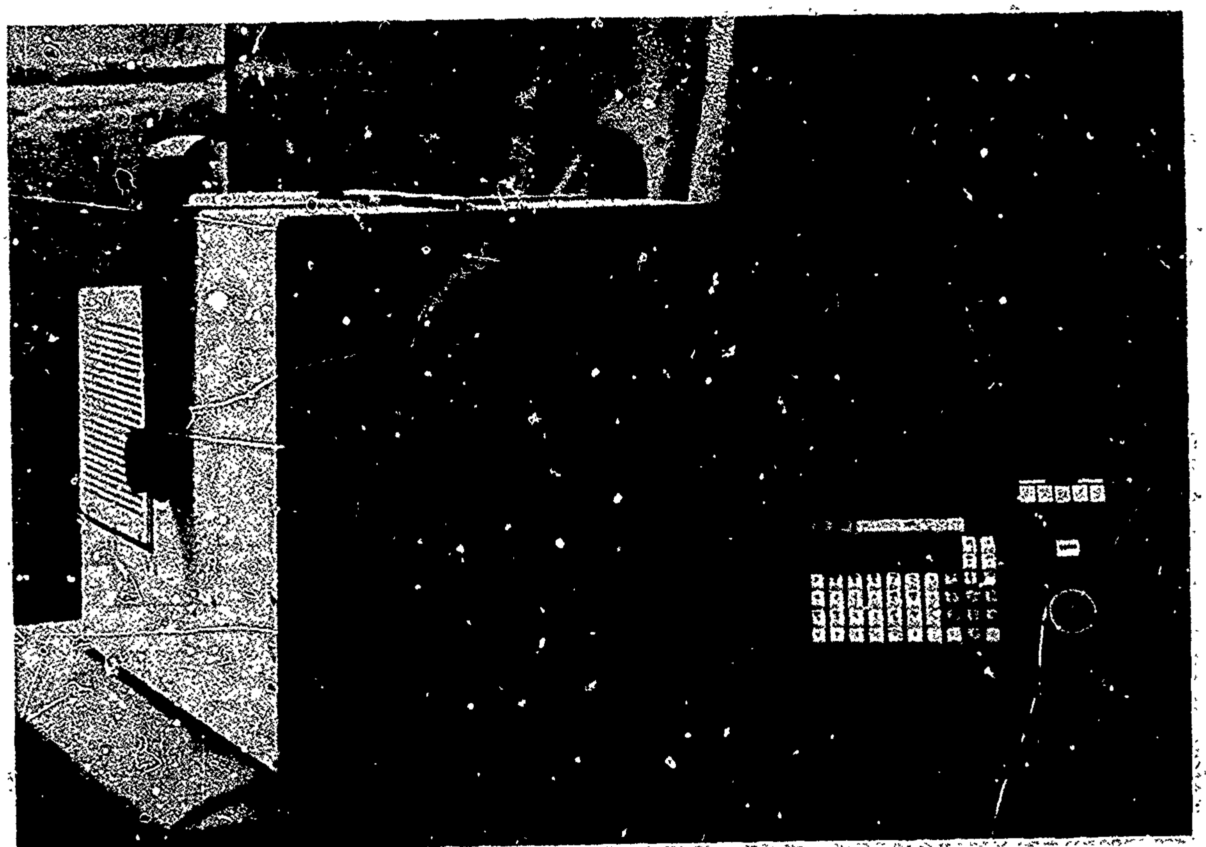

Illustration 1 Tower cab digital display (TCDD) photo

DISCUSSION

D.V.Kyle, UK

Are any resolution problems created by the use of the Rank Order Quantizer?

Author's Reply

Theoretically, we would have a resolution problem with two targets in the rank using 4% P_N or 3 in the rank with 8% P_N. In practice, however, this has not been a problem and resolution is as good or better than with SSR.

EXPERIENCE WITH AUTOMATIC TRACKING SYSTEMS OF THE ROYAL NETHERLANDS NAVY

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Centre for Automation of Weapon
and Command Systems (CAWCS),
Royal Netherlands Navy (RNLN),
Den Helder, the Netherlands.

SUMMARY

This paper deals with the problems encountered and the experience gained with automatic tracking systems for the modern frigates of the Royal Netherlands Navy.

The objectives for introducing these systems are mentioned and compared to the actual results. At the moment we have several years experience with the 3D-automatic tracking system aboard the "Tromp"-class frigates, while for the "Kortenaer"-class frigates shore-based and initial seagoing trials have been carried out with its 2D automatic tracking system for air targets and surface targets. A converted "Van Speyk"-class frigate carrying a system similar to that of the Kortenaer is undergoing integration tests now.

A brief description of some tools used during the design of these systems is inserted to give an idea in which way CAWCS handles problems like this. Finally some attention is paid to the direction of our actual development effort.

1. INTRODUCTION

1.1. Objectives.

The objectives to introduce the on board data handling system DAISY (Digital Automated Information-processing System) on our frigates are:

i) bring the Command Information Center's workload down,
ii) supply the command timely with a digestable amount of relevant and correct information.

To achieve this in a cost-effective way straight-forward solutions are evaluated, and in most occasions the degration with respect to the theoretical best solution is neglectable. In our view the search for simplicity is the best approach in dealing with the constraints imposed by the available memory size, processing time and delivery date. Meanwhile the technical risks are surveyable, and if bottle-necks arise, timely reaction is possible.

1.2. Approach.

Different DAISY's have been introduced on various types of frigates, but the similarity in operator interface -for saving on operator training- and the similarity in software -for saving in development costs- have been regarded conscientious. This approach led to a DAISY-family of close related data-handling systems, only deviating in areas, where necessary due to the characteristics of the type of ship.

Automatic tracking being a subsystem of these DAISY's should follow the outlined directives. So the same set-up has been used for all automatic tracking modules, and deviations were only allowed, if otherwise the performance of the system would be degraded noticeably.

1.3. Design considerations.

Automatic radar data processing can serve the prime objective. We distinguish in this field operator initiated automatic tracking and automatic initiation systems. The latter is the most attractive, if the number of generated false tracks is small and the track-duration long enough. Otherwise the rapid change of the tactical picture will confuse the operator. Furthermore the time to distinguish between true tracks and false tracks must be limited, and the core and processing-time needed must be available. Operator initiated automatic tracking is less complicated mainly because the spontaneous generation of false tracks is absent.

As for both systems track-duration is relevant, some analysis was done in this direction, revealing the sensitivity of the track-duration with respect to various parameters like detection- and false alarm probabilities, measurement accuracies, data rate, filters and target accelerations.

The development of a suitable filter was done in parallel, as the requirements to the filter became apparent during this process.

2. TOOLS

2.1. Filter-development.

In the early development of tracking filters attempts were made to serve two goals. The first is to realize prediction for the next association, and the second is to adapt to the required smoothness for the data-handling system. However in systems with modelling errors, as well as noise - e.g. second order filters for manoeuvring targets- the optimal solution for association is not suitable for the data-handling system. Therefore we created a loop-filter to be optimized for association, while the association process will make available a plot-string for the data-handling filter.

As the loop-filter a sensor oriënted α/β-filter adaptive to "missed looks" and range is used. The adaptivity is similar to that of the Kalman filter. The reached predicted position noise is comparable with the measurement noise, for the association process takes into account the difference between predicted position and the actual measurement, so the relevant parameter is the sum of these noises. The data-handling filter selection depends on the use made of this information. In the present systems the position information is used in the same way as raw radar video, and the same accuracy is acceptable. Only target velocities need further smoothing, accomplished with a first order filter.

2.2. Track-duration model.

The unbranched tracking process can be considered as a Markov chain with state variables bias and noise on the difference signals between predicted positions and measurements. To reach the next stage one of the following events occurs:

i) correct association
ii) no association
iii) association with a "false plot"

The probabilities of these events depend amongst others on the present state, measurement noise, gate dimensions, detection and false alarm probabilities and target behaviour. If for a specific case these parameters are selected, bias and noise on the difference signals after each of these events, which define the next state, and the transition probabilities between the various states, can be calculated by means of fundamental probability theory.

This chain has an innumerable amount of states. This amount can be reduced by deciding that a track will reach the state "lost" after M successive fades or after N successive false associations. A further reduction of the chain is effectuated by stating that P successive correct associations will totally obscure the influence of the preceeding measurements. Finally the Markov chain is made recursive by reintroducing lost tracks (fig. 1).

In this way an irreducible, aperiodical Markov chain with stationary transition probabilities is created. In such a chain the probability of loosing a track is easy to calculate, and the reciproke value multiplied by the measurement interval is the mean track-duration. This track-duration has to be split in two parts: true track-duration and false track-duration. The false track-duration is determined by calculating the track-duration of a track with detection probability zero. In all applications it is necessary to verify that the values of N and P are large enough to make their influence insignificant. This model is oversimplified but it suits the engineering purpose. The objective to maximize the track-duration is reached in a heuristic way, by varying the loop filters, gate dimensions and lost criteria. This can be done for any given set of radar- and target-parameters such as detection and false alarm probabilities, measurement noise, measurement interval and target manoeuvres. For a given system only the measurement interval is determined in a direct way. The other parameters are not constant and can be subject to sudden changes. For the time being estimation of these parameters is not done, because no way was found for reliable turn detection, which causes the severest parameter change. Therefore the systems are made capable of handling a broad class of targets with for instance a detection probability of more than 50%, moderate targets accelerations and a false alarm probability inside the gate ranging from .1% to 20%.

2.3. Conclusions.

The sensitivity research for an unbranched tracking process as outlined above brings out, that more sophistication in filtering does not pay because the optimum is faded away by the broad class of targets. Furthermore it shows, that the false alarm probability inside the gate is the more important factor that governs the track-duration. As the gate dimensions in low data rate systems are dependent of the expected target accelerations, the track-duration can be increased by reducing the capabilities to track accelerating targets automatically. Taken into account that most targets do not turn sharply, and that targets that do make these turns need operator attention anyway, the operator is assisted in the best way by optimising the tracking of moderate accelerating targets.

3. PROJECTS

3.1. 3D-automatic tracking.

About 15 years ago the development was started to create an advanced automatic initiation and multitarget tracking 3D-radar for major ships. The rotating aerial system (fig. 2) of this radar consists of three surveillance antennas, which are capable to produce on a time sharing basis six pencil-beams providing sufficient elevation coverage, and two frequency scanned arrays to serve 3D-tracking. The surveillance system is equipped with a full area plot extractor and the frequency scanned arrays have a range-gated plot extractor. The frequency scanned arrays can be programmed either to do an elevation search scan resulting in an elevation and range measurement or, if the elevation is known, a position measurement scan resulting in an azimuth, elevation and range measurement.

One of the intended operational modes of this system was 2D automatic detection followed by validation, and finally leading to 3D automatic tracking. It was expected that areas with higher false alarm rates had to be excluded from this mode. The exclusion would be an operator task. However during evaluation on a shore-based test site it appeared that under adverse conditions a noticeable part of the coverage had to be excluded, and the control of the exclusion feature would be a complicated operator task.

For the time being this mode is rejected because an operator misjudgement will probably decrease the system performance in the area of main interest. Therefore it was decided to create the better surveyable system of operator initiated automatic tracking aboard the "Tromp"-class frigates. Detection and validation are done by the operator on basis of the surveillance video, while 3D-tracking is done automatically with the computer controlled tracking beams of the frequency scanned arrays.

3.2. 2D-automatic tracking of air targets.

Based on the experience with the complicated 3D-tracking system, the development started to create an automatic tracking system for the "Kortenear"-class frigates, equipped with modern 2D-radars. The data rate of the air warning radar is lower than that of the 3D-radar, but it has a better range accuracy. Therefore the filter-parameters and lost criteria have been adapted. As the control of this full-area extractor is far less complicated, the result is a quite compact tracking module. Shore-based and initial seagoing trials show, that the system performs satisfactory.

With a few changes this module fits to the radar-extractor chain of the converted "Van Speyk"-class frigates. Results of the integration test of this system will be available at the end of this year.

3.3. Automatic tracking of surface targets.

As high data rate is not of prime importance for tracking of surface targets, and plot-extraction for this purpose leads to relative high false alarm rates, range gated plot extraction is used to save computing power. The loop-filter used is matched to small modelling errors, but agile enough to follow target turns. For a good velocity estimation a stale data-handling filter is needed. The performance of this system on the "Kortenear"-class frigates is very satisfactory. The results of the integration of this system aboard the converted "Van Speyk"-class frigates will be available at the end of this year.

3.4. Remarks.

Observations of the operational systems and comments of the users leads to the following remarks:

- The track-duration has to be 10 minutes at least to bring the operator's workload down noticeably.
- The position accuracy of automatic tracking is generally better than that of rate aided tracking.
- Attention should be paid to reach the required velocity accuracy, especially for slow tracks.
- The behaviour of automatic tracking systems should be as transparant as possible for the operator.
- The responsibility for a track should remain with the operator as long as the automatic tracking system is not positive, that it will probably succeed.

- Attention should be drawn to lost tracks.
- Correlation of lost tracks to live video should be facilitated.

Comparing the 3D-system with the 2D-systems leads to the statements:

- As the radiated energy in 3D-tracking (dedicated beams) is not used for search, the 3D-tracking system is rather considered a time shared tracking channel than a track while search system.
- The allocation of the 3D-tracking channel in a multi-target environment offers to some extent the possibility to pay more attention to a specific track.
- A time shared tracking channel is more vulnerable to saturation than a full area track while search system.
- 3D-tracking is less affected by lobing.
- 3D-tracking usually has a smaller acquisition volume, leading to a better signal to clutter ratio.

8. ACTUAL DEVELOPMENTS

In the present systems the performance is mainly limited by the false alarm rates and the detection probabilities. An improvement will be to leave the unbranched prediction process and to adopt multiplot association. However an extreme rough analysis shows, that this will result in an excessive increase in needed computing power and relative little enhancement in performance. Research or experience in this field indicating ways to proceed is very welcome.

Now our research is directed towards the following subjects:

i) Automatic initiation of fast closing targets with a 60 rpm search radar,

ii) Automatic initiation with a S-band phased array radar.

Although these studies are in the initial phase we believe these directions are promising, because the higher data rates will result in a faster validation procedure, and will reduce the plot acceptance gates, which should result in a lower false association rate and longer track-duration.

Vectors indicating the transition probabilities in case of:

i) correct associating, (R),

ii) no association, (Ø),

iii) association with a "false plot", (F).

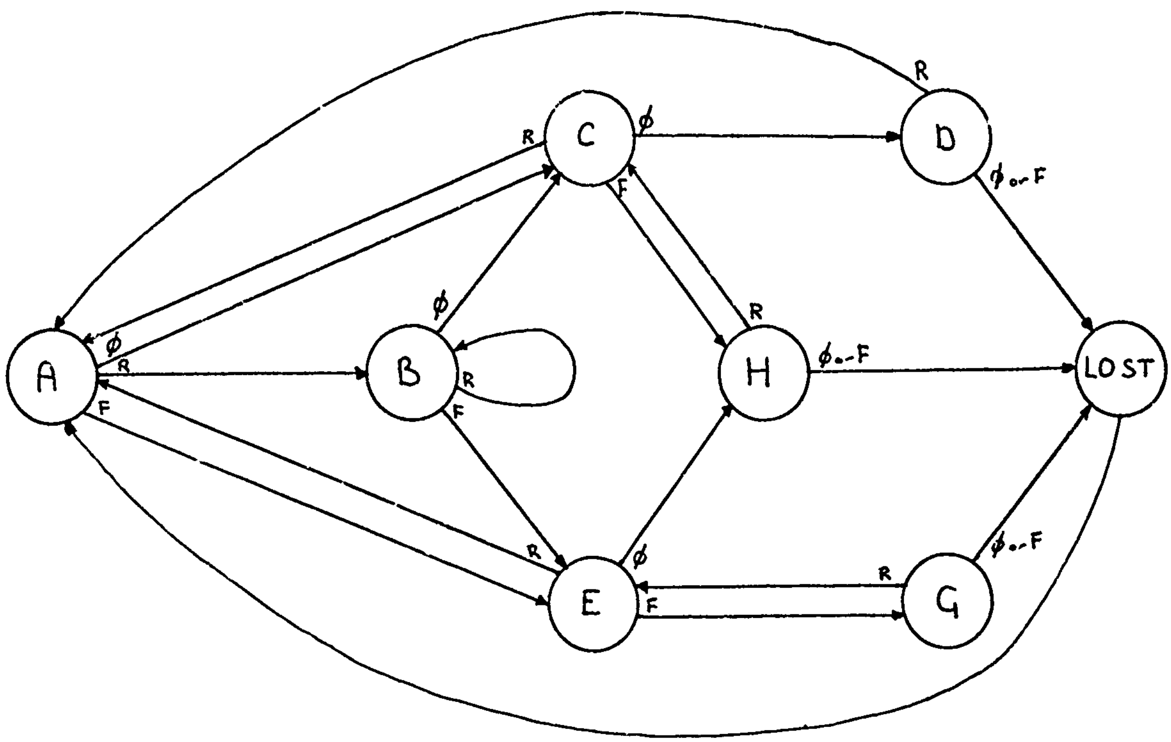

Fig. 1: Simplified Markov chain of a tracking process.

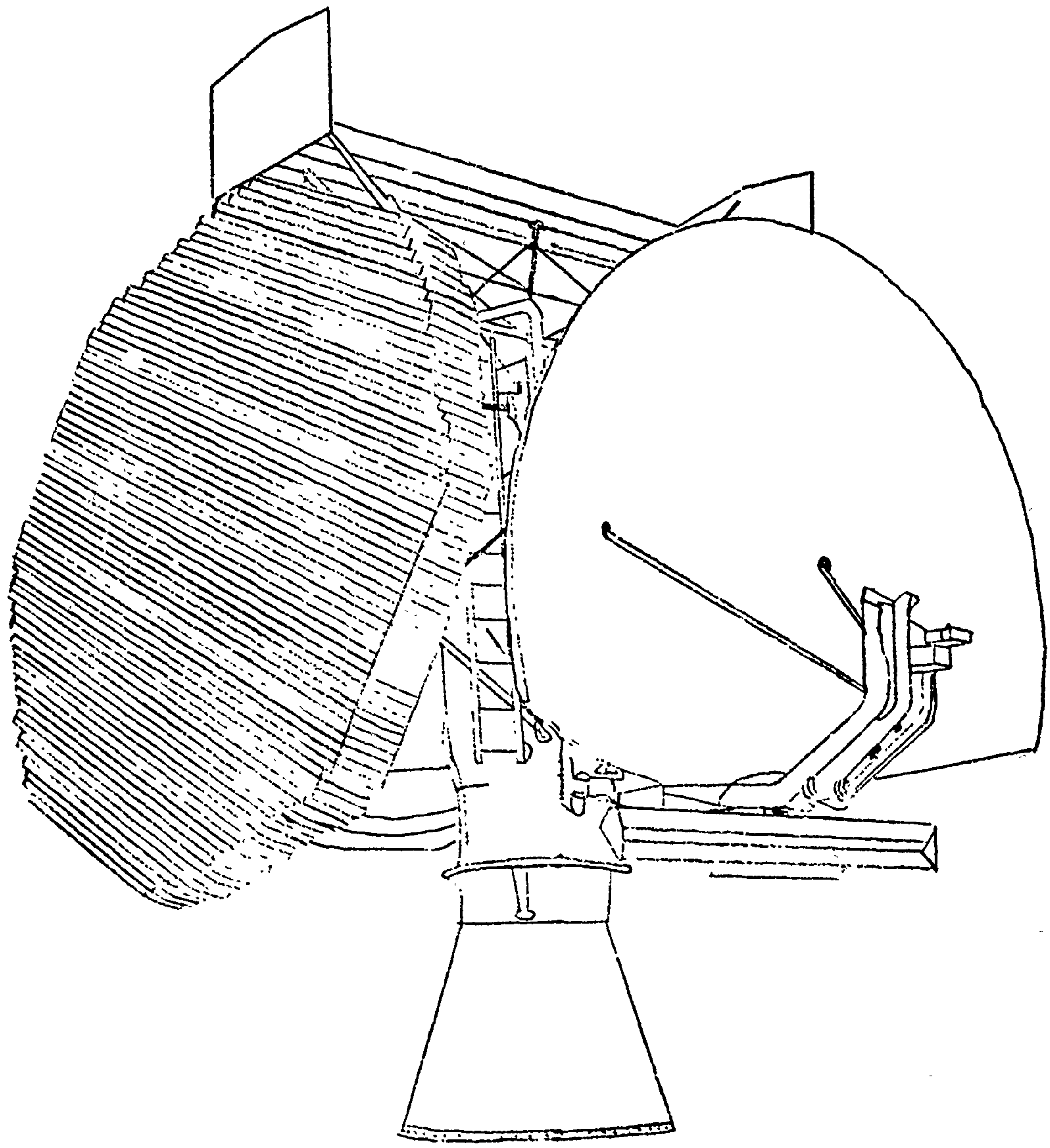

Fig. 2: Aerial system of the 3D-radár.

THE REMOTE RADAR TRACKING STATION

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SUMMARY

Complete hands-off tracking requires a machine that will perform a fine grain mapping of the radar clutter, select Moving Target Indicator (MTI) video in those regions containing clutter and observe targets in the MTI video over the MTI residue while maintaining a constant and homogeneous false alarm rate. Moreover, just as a human modifies his tracking criteria in noisy regions, an automatic tracker may emulate the human by looking into the clutter maps and obtaining the "clutter state" of the neighborhood of the track's predicted position. Radar plot extraction and tracking are thus seen as inextricably interrelated processes. The Remote Radar Tracking Station (RRTS) is a machine, designed and field tested, to solve this problem.

INTRODUCTION

Our notion of an ideal radar processor is essentially abstracted from our own performance in watching radar data on a Plan Position Indicator (PPI). We can recognize clutter and noise and distinguish targets at an acceptable false alarm rate. We integrate targets over several scans until we form a reasonable estimate that a track exists. When targets pass over cluttered regions, we can use MTI video and, often, even in the presence of imperfect cancellation, make out the target and start or continue tracks. Tracks passing through badly cluttered regions can receive special treatment since we know the clutter is there and can wait for the target to reappear if we can see that the clutter is of limited extent.

While humans must limit their attention and superior processing ability to a few targets and produce fairly noisy position estimation, machines are envisioned that can apply humanlike techniques of detection to the entire surveillance volume with accuracy. If it were merely a matter of separating aircraft returns from receiver noise, the problem would be immensely more tractable. The principal problem is, however, recognizing and contending with clutter. The radar picture contains quite irregular regions of ground-clutter masses, point source clutter and distributed clutter. This clutter varies in amplitude and variance, not only spatially but temporally (Nathanson and Reilly, 1967). Radar sets typically provide an MTI video to eliminate and see through the clutter. This MTI is effective inversely proportionally to the amplitude of the clutter, the degree to which the clutter velocity is displaced from zero, and the clutter variance. Originally, MTI video was selected on a range-gated basis; later systems used positionable range-azimuth gates. The use of grossly sized gates for the selection of MTI video is undesirable since MTI circuitry, at its best, introduces losses, and all too often in the real world the MTI circuits are casually aligned. Use of MTI in these kinds of systems should therefore be restricted to precisely those fine grained range-azimuth regions that require it. Thus, an Automatic Clutter Mapper (ACM) is required to have the capability of partitioning the surveillance volume into tens of thousands of range-azimuth cells and performing independent clutter tests within each cell.

Digital detection of radar targets is a several-step process. The first step compares the video returns against one or more threshold levels in quantizers. The outputs of this step are input to an azimuth edge detection process whose output, in turn, feeds an azimuth width detector whose output subsequently feeds the tracker for final detection. The setting of the thresholds determines the false alarm rates of the entire process. When normal video is used, a threshold can be employed which is set as a function of noise events sampled out at radar range maximum time. When MTI video is employed, the threshold used should be a function of the MTI residue surrounding the range-azimuth cell of interest.

In order to have a meaningful automatic detection and tracking system, Constant False Alarm Rate (CFAR) processes must exist which will produce a constant and homogeneous false alarm rate in all regions of the surveillance volume. It is obviously desirable that these processes harm the probability of detection as little as possible. In the Remote Radar Tracking Station, the Automatic Clutter Mapper (ACM), and the MTI Residue Mapper (MRM), are the means wherein this goal is accomplished. (4-3 Figure 1)

REMOTE RADAR TRACKING STATION (RRTS) DEVELOPMENT

From the outset, the RRTS was designed to jointly address the radar detection and tracking problem. The intent was to identify the mechanisms humans used in tracking aircraft and apply these same techniques in hardware. By implementing the detection, mapping and tracking functions in a single distributed processor, constructed of high speed programmable processing elements, and taking advantage of the memory technology that exists, it was feasible to implement the above-mentioned heuristics. Moreover, the developed machine was highly maintainable despite the complexity of its many tasks.

The RRTS (4-3 Figure 2 and 4-3 Figure 4) is a programmable distributed signal processor, which, interfacing with 2D search radar sets, accepts the analog triggers, azimuth data and video, and outputs digital messages giving the cartesian position and velocity of aircraft flying within the surveillance volume. Included within the equipment is IFF processing logic that, along with a collocated secondary radar (IFF set), determines the position of IFF responding aircraft, extracts their IFF codes and correlates these position reports with the radar-derived reports. The outputs of the RRTS – which can be basic plot data, if desired, rather than full tracking data – are put onto a digital data link via a self-contained communications processor.

The azimuth converter accepts synchro data (single or multiple speed), resolver, or Azimuth Change Pulse (ACP) and north mark inputs and converts this information to binary azimuth, distributing the azimuth throughout the RRTS. The radar range zero trigger is input to the system which aligns the system clocks to the trigger and produces an internal range maximum trigger.

The quantizer card contains quantizers for the normal video input and for an MTI video input. Threshold control for the normal video quantizers is provided by the CFAR Unit which takes samples during the range maximum time and servos a threshold voltage to maintain the desired false alarm rate. Threshold control for the MTI video quantizers is provided by the MRM. A separate map is provided for each MTI quantizer.

Selection of the quantizer video outputs into the digital detection chain is controlled by the ACM. The ACM determines when normal video is to be used, when MTI video is to be used, or when no video is to be used (i.e., excessive point source MTI residue). The digital detector also receives IFF position and code data from the IFF processor. This data is correlated in range and azimuth with the radar reports, and the combined report is passed along to the tracker.

The tracker correlates the inputs with its track file establishing a new potential track when no correlation can be made on a new input. All tracks in process have their position fed back to the Clutter Mapper where the clutter state surrounding the position of the report is ascertained and reported back to the tracker to aid the tracking process. Track outputs (or raw reports, if desired) are passed along to the communications processor which formats the data and interfaces with a modem for transfer to a remote (or local) user.

The maintenance monitor injects targets and clutter into the processor and monitors false alarm rates, map sizes and other process information to detect real-time failures. The maintenance monitor signals faults to the control panel and is then used to aid the fault isolation process.

AUTOMATIC CLUTTER MAPPING

The ACM (4-3 Figure 5) partitions the surveillance volume into small range-azimuth cells and for each of these cells maintains a word in memory which indicates the clutter state of the associated range-azimuth (clutter) cell. Since the clutter state of the world changes constantly due to weather and propagation changes, clutter mapping must be a dynamic process that responds quickly enough to prevent the leading edge of weather from producing a front of false alarms without mapping out desired targets. The clutter to be mapped may be thought of as forming a two dimensional map of false alarm probabilities which slowly change with time. High probability points in this representation are frequently surrounded by low probability contour lines. The clutter mapper is essentially a sensitive digital detector operating over multiple scans (i.e., slow time constant) seeking to determine within each cell if clutter plus noise exists, as opposed to noise alone.

The surveillance volume is partitioned uniformly into 65,536 range-azimuth cells. The partitioning is performed automatically upon system initialization and is a function of the radar beam width and pulse width. The azimuth cell sizes are set to approximately 0.6 to 0.7 of one beam width and the range cell size set to an integer multiple of the pulse width.

The borders of cluttered regions may tend to produce false alarms, despite the clutter mapper, since clutter in these regions may possess a probability of threshold crossing lying in the intermediate region of the statistical test's Operating Characteristic curve. To account for this phenomena, the selection of video by the ACM is done on an overlapped basis. Thus the video gated into the digital detector in any cell is determined by the clutter state of that cell and its eight neighbors in range and azimuth.

If a clutter mapper is used in a stand-alone environment, there is a real hazard of tracks mapping themselves out. This will certainly occur for very slow moving targets; moreover, it will tend to occur when aircraft in numbers fly over the same air route. A human does not have this problem since he is able to readily distinguish aircraft from clutter (i.e., the human "tracks" the aircraft). The collocated tracker is thus seen as necessary to stand-alone clutter mapping. The tracker feeds back position reports on all targets being tracked to the clutter mapper and sets the suppress bit in the clutter word. This bit, when set true, prevents the clutter mapper from changing the clutter state on the next scan past cell.

MTI RESIDUE MAPPING

Quantizer threshold control for the MTI video must be a function of the local MTI residue. "Residue" here is defined as the usually noise-like survivors of the MTI process which are not the desired aircraft echoes and exceed the average receiver noise level. This residue is produced from radar instabilities, poor radar alignment, high amplitude clutter and clutter from moving sources (weather, dust storms, birds, etc.) (Skolnik, 1970). The residue in a region is often relatively constant, and moving targets flying through the region can be easily detected over this residue. Efforts in the past to automaticaly produce a threshold voltage which would contour the residue have involved some form of integration on the MTI video. This has been done on a single sweep basis (e.g., Mean Level Detection) and a multiple scan basis, in discrete range-azimuth cells. These systems usually provide a manually controlled offset voltage to produce the actual threshold voltage. A fixed offset will not produce a constant false alarm rate since the clutter variance is unknown.

The MRM of the RRTS consists of a single fine grain (96,000 cell) map and three coarse-grained (approximately 4,000 cell) threshold maps. (4-3 Figure 6) The fine grain map effectively integrates the analog MTI video in small range-azimuth cells, often close to the resolution cell of the radar. Since the RRTS requires two detection thresholds plus a threshold for the ACM for each video, three independent threshold maps are maintained. Each of these maps partitions the surveillance region into roughly 3 degree azimuth cells by 6 mile range cells (assuming approximately 200 miles range). During each antenna scan over the cell, an accumulation is made on the quantizer crossings from each of the quantizers. The number of crossings is compared with the desired false alarm rate for that quantizer, and, if over, the threshold value is increased; if under, the threshold value is decreased. The actual threshold voltage used by each quantizer is the analog sum of the fine grain stored history and the coarse-grained threshold map history. Thus, each region of the surveillance volume will possess a contoured threshold voltage whose actual amplitude is an optimum function of the local clutter variance. (4-3 Figure 7)

THE TRACKER

An adaptive, or variable, $\alpha\beta$ tracker is employed in the RRTS. For single radar inputs occurring at a constant data rate, this has been shown to be as effective as Kalman filter implementations as long as it is supported by an intelligent correlation gating mechanism. All tracks have a pair of correlation gates associated with them. Input reports that fall within the inner gate give evidence that the system is smoothly tracking. Inner gate maximum values are set at ± 2 miles but are usually much smaller. The outer gate is shaped to correspond to an equal probability contour for aircraft maneuver and is, in fact, a maneuver detection gate. Reports falling in the outer gate are not used for position correction unless the track is declared "in maneuver". Correlation of an input report with a given track additionally utilizes IFF codes and radar or IFF height.

A track quality number (TQN) is kept with each track and can be used both internally and externally as a proper measure of tracking performance. This number is an integer which is allowed to range from 1 to 7. Upon track initiation, it is set to a 4. Thereafter, each occasion of two successive inner gate hits increases the number by 1, and each occasion of two successive inner gate misses decreases the number by 1.

AUTOMATIC TRACK INITIATION

Historically, automatic track initiation schemes have operated blindly with respect to the radar environment. That is, the tracker receives "mathematical points" from the target detector and then attempts, over a period of several scans, to assemble these points into a track. If the "points" were caused by a valid target flying in a clutter free region, then an algorithm might be readily devised to initiate a track. That same algorithm may, indeed, produce copious false alarms if a region of the surveillance volume is cluttered and produces a high rate of clutter generated false reports. If the detector can guarantee no false reports or a truly homogeneous and low false alarm rate, then a single initiation algorithm is reasonable. Such a guarantee is rare. Essentially, one must have a very good MTI. When one interfaces with extent radars, regions of excessive MTI residue which wax and wane are more likely to occur.

The ACM and the MRM are designed to whiten the clutter residue to the greatest possible extent given the necessity of retaining the original MTI receivers. Nonetheless, this process is not perfect. The automatically developed fine grain clutter map is, however, a record of exactly where clutter produced false alarms are likely to occur in the surveillance region.

The clutter map stores three kinds of clutter states: use normal, use MTI, and CENSOR. The simple presence of several "use MTI" states in a region certainly indicates that clutter is present. The presence of CENSOR states in this region indicates that the MTI and the residue mapper have not been effective for this cell, and clutter false alarms have been produced, generating the CENSOR cell. As clutter may be envisioned as modeled by a probability contour map, the presence of a CENSOR cell implies that a surrounding region may be producing false alarms, but at such a sufficiently low rate that CENSOR cells are not built up. Nevertheless, a sufficiently large number of such low probability cells will produce clutter false alarms. These considerations give rise to our track initiation strategy.

Each track's predicted position is fed back to the clutter map. Fifteen clutter cells are checked around the reported position. This includes the present azimuth cell, plus and minus one azimuth cell, and the present range cell, plus and minus two range cells. Within the map, the normal state is represented by a zero, the MTI state by a one, and the censor state by a two. As each cell is checked, the sum of the internal states is accumulated. The final accumulation may vary between 0 and 30. The number is fed back to the tracker and is stored in the track file with the track and is used to select an initiation algorithm specific to this track.

PHYSICAL IMPLEMENTATION OF THE RRTS

The RRTS has been implemented with twenty-seven 8 in. by 8 in. circuit boards as a programmable distributed processor using the Building Block Processor (BBP) (4-3 Figure 5) as the processing element. The BBP is a single circuit board high speed processor constructed of standard low power Schottky MSI and LSI. It processes a 12-bit data word, has 8 general registers, a 4096-address data memory and a separate 4096 address instruction memory in a read only memory. The instructions are 48-bits wide and allow considerable processing to occur in parallel. All instructions are executed in 500 nanoseconds clock time.

The RRTS has been implemented with 9 BBPs plus 9 additional logic board types. All instructions in all BBPs take exactly one clock time, and all machines run off the same clock. All BBPs in the system are interconnected in a single continuous loop with each BBP being a node on this loop. Some BBPs are interconnected in "star" fashion, and real time intercommunication takes place between these machines on these paths (4-3 Figure 8). The radar trigger is used to synchronize the system and time an intersystem transfer on the single loop. The path between units allows specific data from any one BBP to be distributed to any other BBP in the RRTS as required.

Besides the obvious virtues of simple construction, ease of modification and function addition, this distributed processor implementation has produced a system with automatic fault isolation to the single replaceable circuit board within seconds to a 95% confidence level. (Hiner, 1976)

RRTS STATUS

The algorithms and techniques described in this paper are operational. The system has been tested with several different radars at sites in California, Texas, and Florida. The RRTS has demonstrated its ability to operate as a stand-alone, completely automatic, tracking station. It is currently operational at Litton laboratories in Van Nuys, California.

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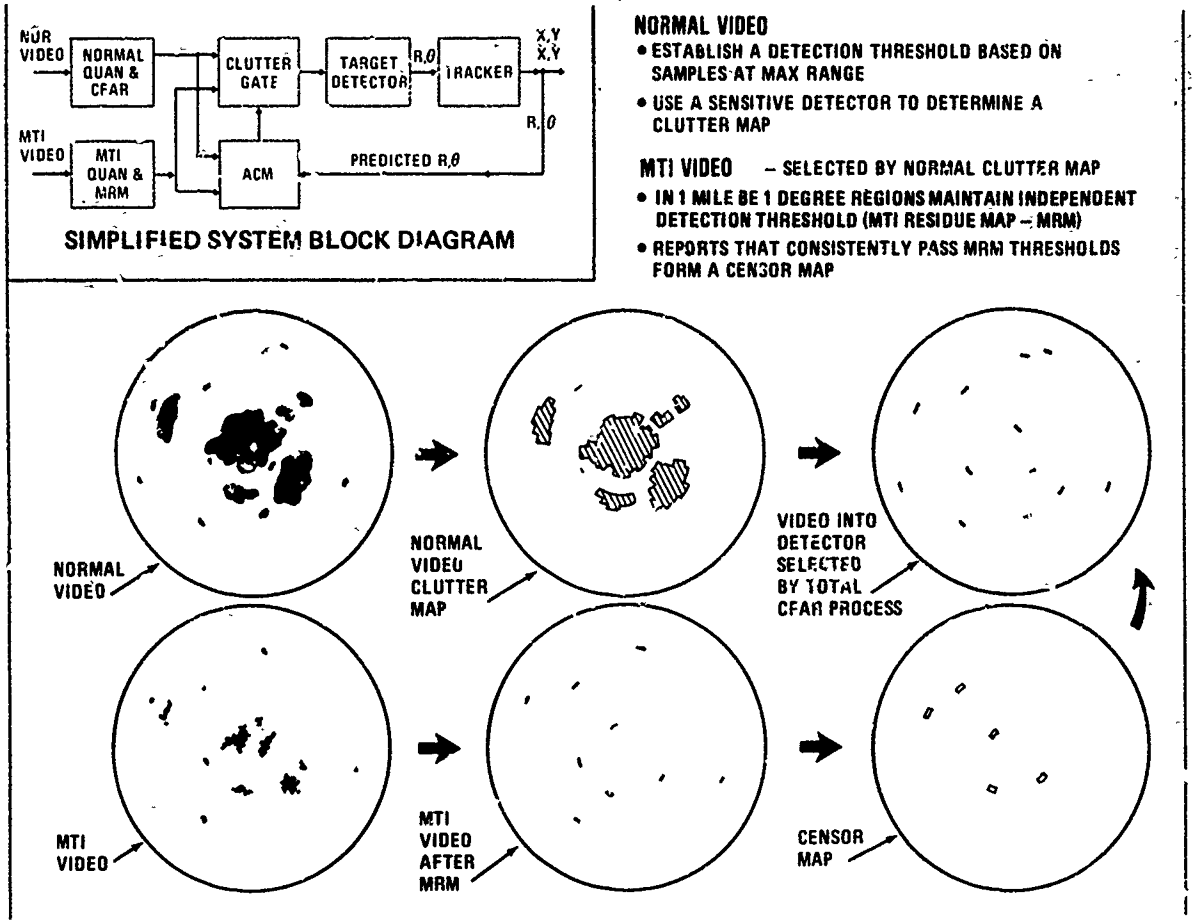

Figure 1 System CFAR Processing

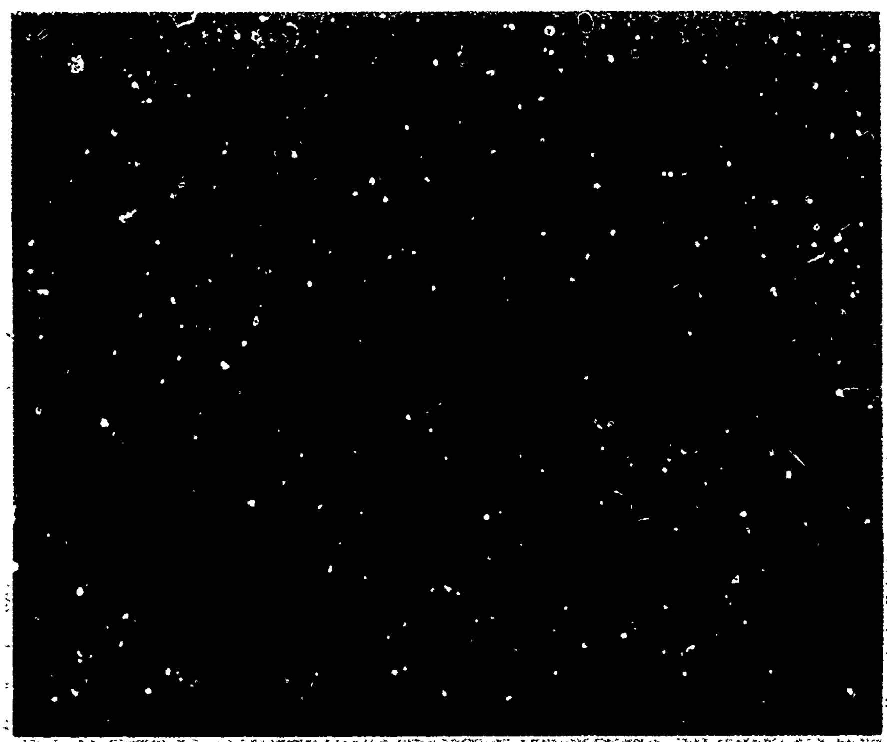

Figure 2 The Remote Radar Tracking Station

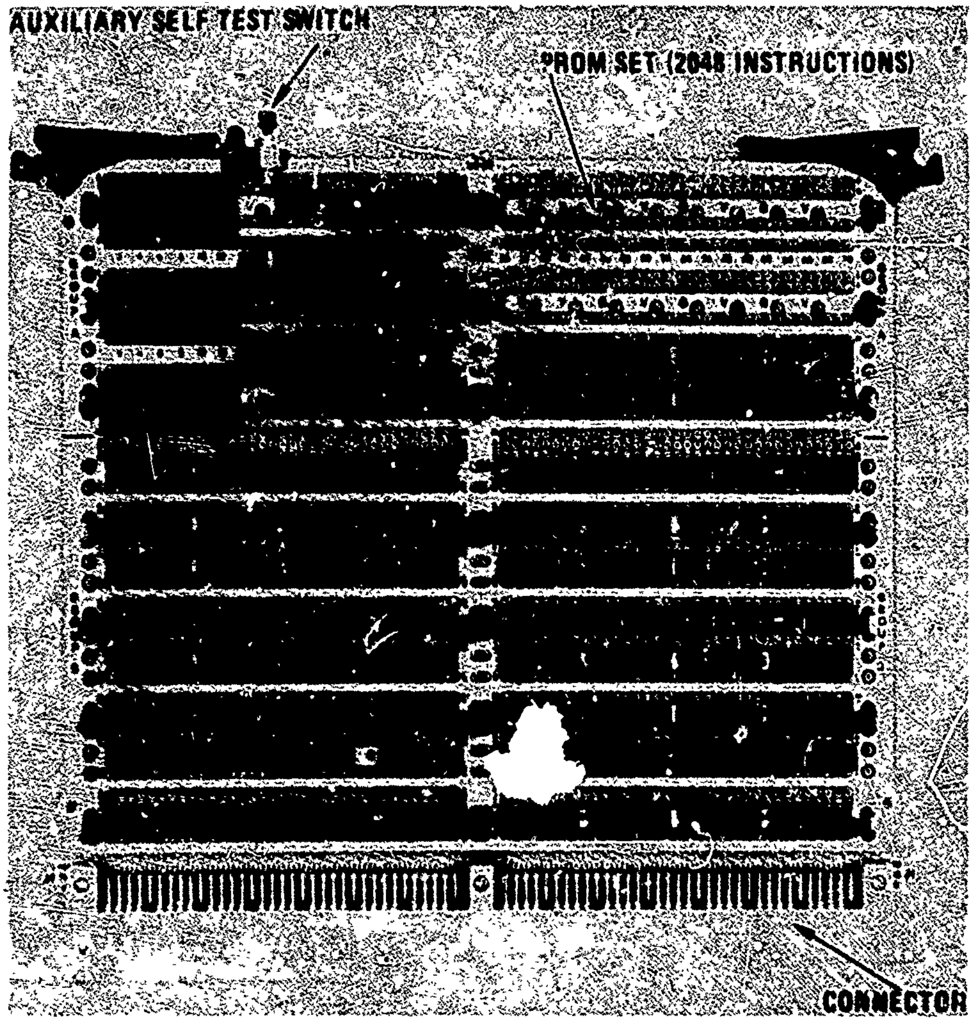

Figure 3 The Building Block Processor

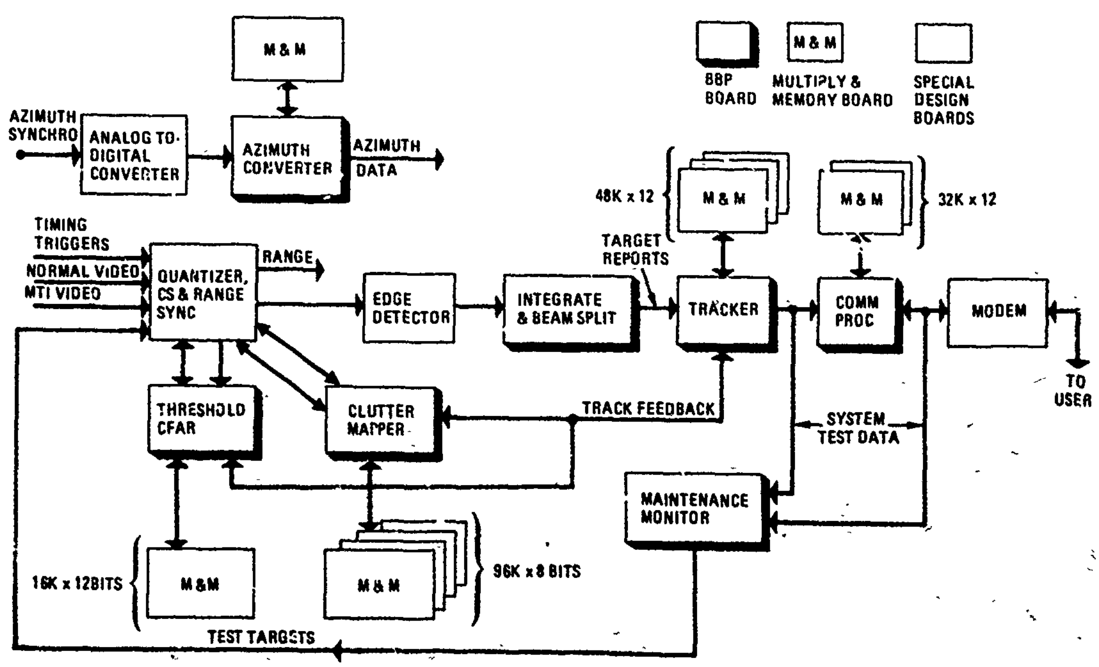

Figure 4 Functional and Card Block Diagram of the RRTS (Sans IFF)

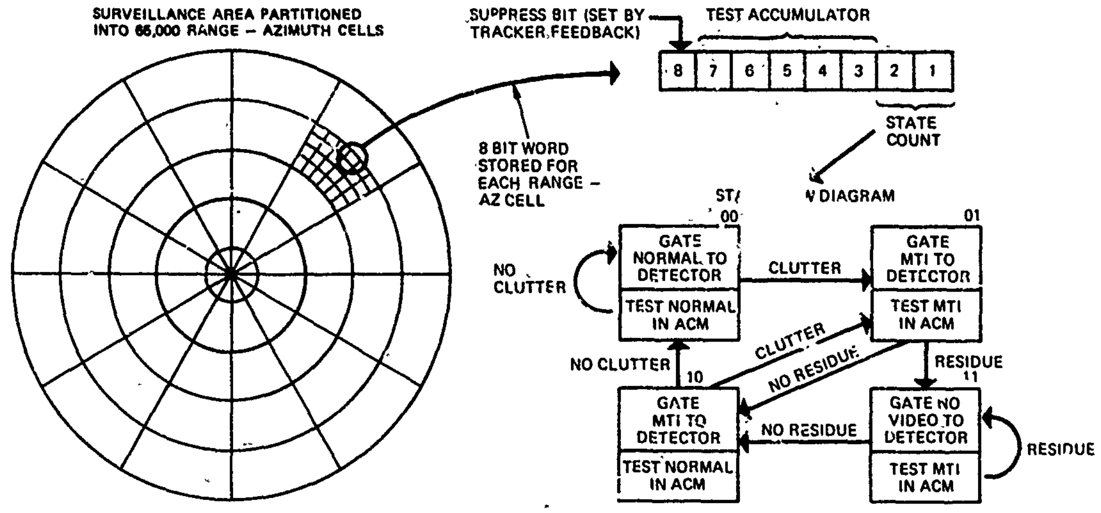

Figure 5 ACM Clutter Cell and State Count Flow Diagram

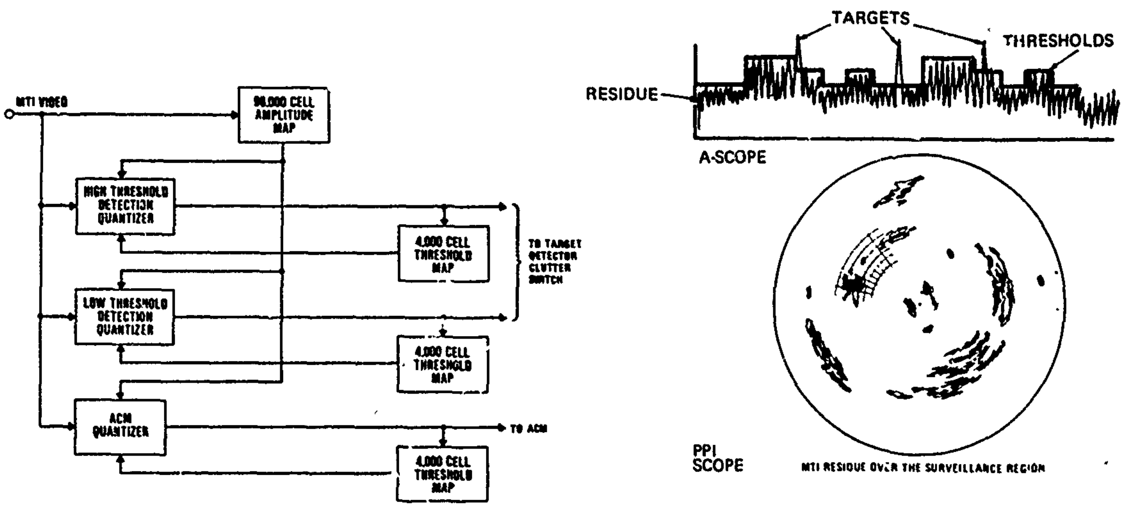

Figure 6 MTI Residue Mapper

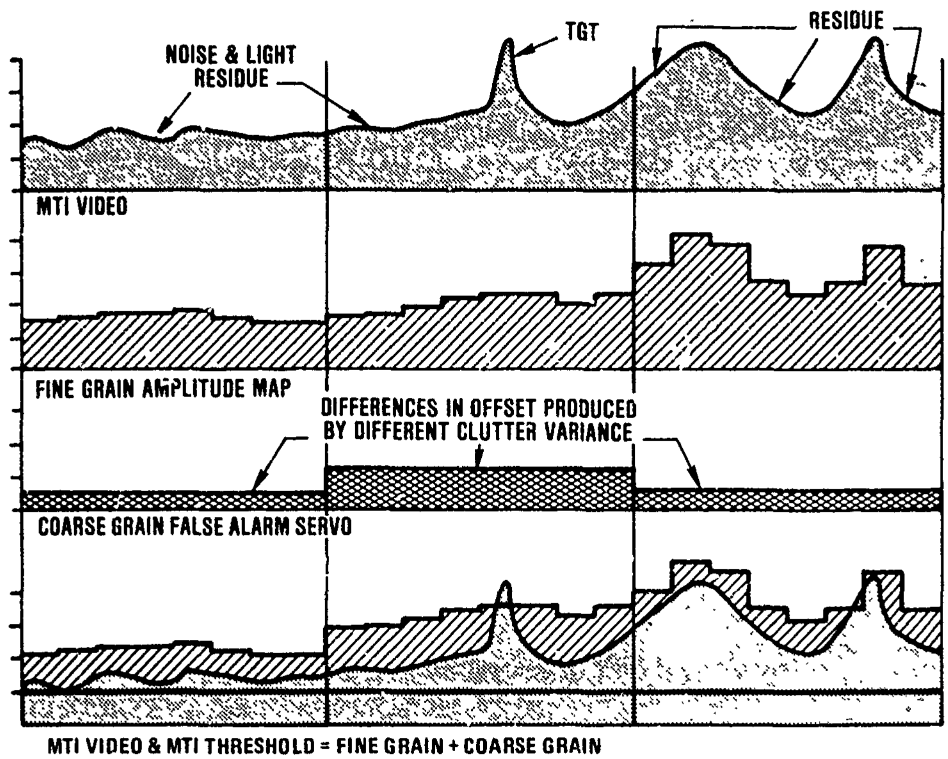

Figure 7 Fine Grain MTI Residue Mapping

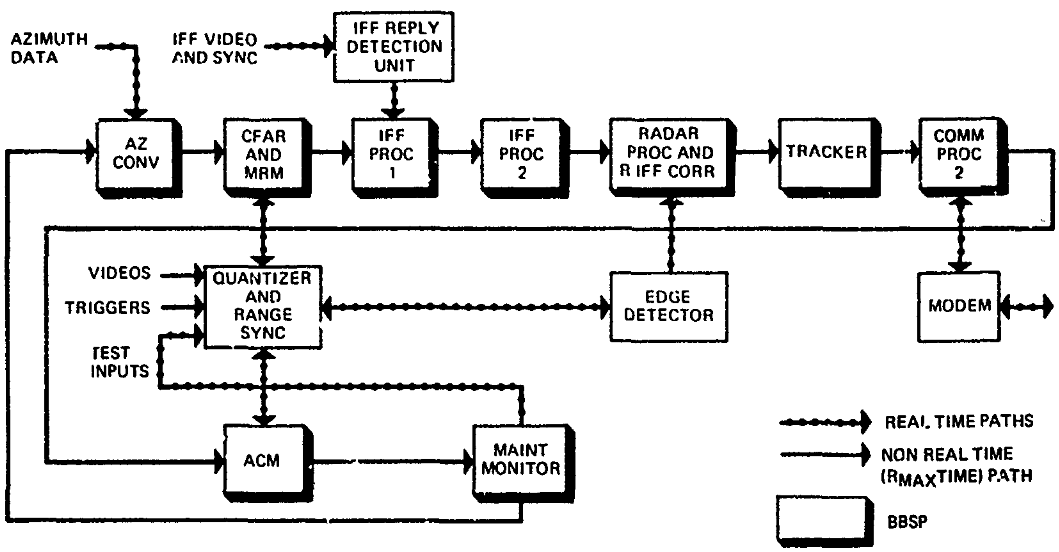

Figure 8 RRTS Data Paths

DISCUSSION

J.R.Moon, UK

Have you any idea of the extra processing load required to handle a cardiod maneuver gate compared with a more usual rectangular gate?

Author's Reply

In the RRTS, the machine execution speed is 0.5 μsec for all operations, including multiplies. We can, in fact, do an indirect memory access, multiply the accessed work with a word stored in register and store the answer in another register, in 0.5 μsec total time. Thus, the required arc-tangent calculation can be performed in about 10 μsec. The actual cardiod is approximated in table and is accessed as a function of the updating report's position with respect to the track's heading. The access is table lookup and the accessed distance is quickly scaled as a function of the individual track's outer gate size. Actual test of the cardiod is performed only on reports that fall within a circular outer gate surrounding the track's predicted position and the required computation time is less than 30 μsec.

G.Binias, FRG

Does the time necessary to transfer data from the clutter mapper to the tracking system create a problem?

Author's Reply

No. We can exchange data between the clutter mapper and the tracker at the rate of several thousand tracks per scan.

E.Hanle, FRG

How do you select the thresholds and factors in your clutter map and threshold control system?

Author's Reply

Quantizer detection thresholds are made a function of the measured hits per beamwidth and were originally obtained via extensive detector simulation.

E.Hanle, FRG

Is the target position error influenced by the clutter map and threshold control system?

Author's Reply

In regions using MTI, the azimuth estimation error is somewhat greater, generally producing slightly larger inner tracking gates. Also, the clutter mapper can shave off edges of targets as they fly near clutter areas; however, tracker feedback can predict this.

E.Hanle, FRG

Can you handle weather clutter as well as ground clutter?

Author's Reply

Weather clutter is handled very nicely by this system; especially as targets can often be seen above the weather clutter MTI residue.

D.V.Kyle, UK

Do you employ the clutter map to modify the rules of Primary/Secondary radar correlation and combinations?

Author's Reply

No, as I'm not certain this would produce any advantage.

E.Brookner, USA

For what system or systems is the RRTS intended?

Author's Reply

Any application where pulsed 2-D (or some 3-D) search radars need to be remoted. The machine should also be useful for local automated tracking. It should be stressed that the RRTS is designed to operate with existing radars and without modification to these radars.

BASIC CONCEPTS OF RADAR DATA PROCESSING IN THE S T R I D A

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SUMMARY

Radar data processing in STRIDA is carried out by three types of processing :

- extraction, which digitalises, extracts and filters radar information,

- tracking, which elaborates and updates the group of tracks for each radar,

- merging, which enables the establishment of the general air traffic chart.

These functions are entirely automatic and are implemented in the different network centers.

The process of initiation and update of tracks is performed in two steps : firstly at a mono-radar level, and then at a multi-radar level.

Concerning initialisation, this technique gives the advantage of limiting the number of false tracks while being sure of creating every new track.

Concerning the upkeep of tracks, this technique enables the establishment of the general air traffic chart by dynamically choosing the best radar detection for each track.

Finally, the method used has permitted the realisation of a high quality and very flexible system whose performances have been continually improved.

INTRODUCTION

The STRIDA (System of Transmission and Representation of Air Defense Information) is a system of resources which permits the automization of operations necessary for the air defense of the French territory, in such a way as to supply information required to react in real time upon request.

The system is composed of the following elements :

- computers

- material for visualisation and dialogue

- transmission lines

One of the principal objectives of the system is to present to Air Traffic Controllers the image of high and middle altitude air situations ; this is carried out automatically by a chain of processing which handles data delivered by a group of bi-dimensional, tri-dimensional and altimeter radars.

In the first part of this exposé, we shall present the principal caracteristics of this processing chain, firstly from an organization viewpoint, and then from a functional viewpoint.

In the second part, we shall put the accent on the principal logic used in the process of automatic initialisation, and also in the process of update and tracking of the air situation so created, in such a way as to put into evidence the advantages of the logic used.

Finally, in the third part, we shall look into the method which was used to produce this system, the flexibility of which has permitted continual performance improvements over the years.

I.

Firstly, therefore, we are going to describe radar processing itself.

Most of the processing carried out below each of the radars is computer processed by programmed or microprogrammed digital calculators.

The establishment of the air situation in the system consists of creating and updating a data base which contains information on the detected aircraft ; this is carried out by three types of computer processing :

- extraction, which consists of digitalising primary and secondary radar information, then extracting and filtering this information in such a way as to create plots, i. e. at each scan, information on position, quality, IFF/SIF, of the different aircraft.

- automatic tracking, the aim of which is to update a data base containing aircraft caracteristics, (position, speed, cape, IFF/SIF), for each radar.

  Therefore, starting from radar plots, tracking elaborates the elementary tracks corresponding to the aircraft detected by the radar. It is clear that for a single aircraft, there can exist several elementary tracks obtained by several radars.

- multi-radar processing, called Synthesis in the STRIDA, the aim of which is to update a data base containing the caracteristics of aircraft detected by a group of radars connected to the same center. Starting from the different elementary tracks, the synthesis then elaborates a data base of synthetic tracks in such a way that a single aircraft can only correspond to a single synthetic track in the system.

Since the STRIDA is a linked network, the different processes described above are used in two types of centers :

- CDS's (Center for remote detection), equipped with radars which ensure the detection, the extraction and the transmission of plots.

- CDC's (Center of Detection and Control), which receive the different CDS plots, and which carry out tracking, synthesis, presentation of information to Air Traffic Control, as well as dealing with functions concerning control aid and air defense.

  Since the CDC's are also equipped with radar, they ensure the "CDS local" function ; the "local" plots are transmitted to the central processing calculator in the same way as the "CDS remote" plots.

Due to overlapping of detection zones in certain radars in the system, the problems of establishing the air situation in the CDC's are principally linked to the initialisation and the automatic updating of the synthetic tracks in such a way as to avoid false tracks and to ensure that a single aircraft corresponds only to a single track.

We are now going to see what logic permits the resolution of these problems.

From a functional viewpoint, multi-radar processing is carried out in two stages :

- the establishment of the elementary air situation detected by each radar, in other words, for that radar :

  - automatic extraction and filtering of plots,

  - automatic initialisation of elementary tracks from primary and secondary plots,

  - automatic tracking of the so created tracks, with the possibility of automatic suppression by tracking or synthesis decision.

  All these processes are carried out in a system of co-ordinates centered on the radar concerned.

- establishing and presentation of the air situation detected by the different radars connected to a CDC, i. e.

  - taking into consideration the elementary tracks as they are created or updated,

  - automatic initialisation of synthetic tracks,

  - automatic updating of synthetic tracks by optimal exploitation of the different available information,

  - presentation of synthetic tracks to air traffic controllers.

  This processing is carried out in a system of co-ordinates connected to the processing center, (generally, the system corresponding to the local radar), and in a time system connected to the local radar ; in other words, depending on the radar which detected the aircraft, track positions may necessitate an updating in time in order to present a coherent image to the

Air Traffic Controller.

II.

Following this general description, we are going to show the advantages provided by this method, and also to explain the reasons why it is optimal.

Concerning the process of automatic initialisation, we see that it is situated at several levels within the system ; it is necessary therefore to point out first of all that the quality depends essentially on the coherence between the different processes.

Of course, the optimisation of each element in the chain conditions the final result, i.e.

- extraction must be of very good quality, well adapted to the different radars, completed by an automatic filtering logic to allow the suppression of a maximum of false plots, and regulated in such a way as to supply all plots in a clear area.

- the initialisation of elementary tracks must be complete ; at this first level of creation, association tests are carried out on all plots which have not been recognised by tracking as corresponding to an existing track. Any possible new elementary track is initialised whatever its position or quality.

- the second initialisation level must carry out a filtering : in point of fact, the creation of a new synthetic track is carried out by taking into consideration the existing situation and the position of the track compared to a zone dependant on the quality of radar detection.

- this logic must finally be completed by the possibility of automatic suppression of bad quality tracks.

This two level method of initialisation therefore permits a more flexible track initialisation. Compared to a mono-radar system, it enables the taking of a decision to create a new track by taking into consideration the quality of the detection and by having a better knowledge of the existing situation.

In the same manner, the process of updating synthetic tracks puts into play several processes and necessitates, firstly, a very complete optimization of mono-radar processing, obtained in the STRIDA by :

- precise and flexible extraction limiting detection gaps to an utmost,

- a very performing and "intelligent" tracking with maximum exploitation of the available information at each radar scan, together with being capable of automatic modification of a previous decision since become unsatisfactory, taking into consideration the latest information.

- tracking adapted to all aircraft types, including rapid manoeuvring targets.

- special tracking processes destined to resolve difficult problems of nearby aircraft, (flight interception, flight formation, combat).

What is more, actual multi-radar processing allows the improvement of tracking quality since the synthesis carries out an automatic choice of the best available detection at a given moment for each synthetic track ; for a given aircraft, this choice is made at each update of an elementary track corresponding to that aircraft, and it is the best quality track which serves as a reference for the associated synthetic track, taking into consideration the priorities linked to the CDS's and to the position of the aircraft compared to the zones of more or less good detection.

This logic allows maximum profitability of the multi-radar system by ensuring the continuity of track evolution in using the best detection for each track.

III.

In order to complete the description of the elements having been used to make STRIDA a good quality system, it is fitting to associate the principals and methods applied for its realisation to the technical concepts which we have just described.

One of the principal qualities of the STRIDA, is its flexibility ; all the operational functions (extraction, tracking, synthesis), are programmed, or in part, microprogrammed. Of course, this has permitted to adapt processing to technical evolutions, but also to reply to new user needs with an easy method.

Another important fact to point out is that all the organizations concerned with the development of STRIDA, participate in the definition of the functions as well as in modification decisions ; these organizations are : the Technical Services of the French Air Force, technical and operational personnel of the French Air Force, and the personnel of Industrials having supplied materials and programs. This permits the study and implementation of optimal technical solutions, taking into consideration operational needs.

Moreover, the above fact is enhanced by the existance of an experimental processing center, disposing of technical methods identical to those of the operational centers. This permits the testing of materials and programs in a real environment.

This center has proved to be particularly useful for the implementation of the radar processing chain, and, for example, resolving the problems of patrol flights.

It is also in this center that system improvements are experimented before being placed in operational centers.

Finally, the testing and regulating of the different functions were made possible thanks to the development of powerful test and analysis methods at all processing levels of the chain ; in particular, these methods permit the recording of fugitive phenomenon connected with extraction or tracking, and to restore it in such a way as to supply and study data completely.

IV.

In order to illustrate the preceeding description, we can give several precisions on performances as well as on the materials.

The calculators used in the STRIDA are IBM 360 and 370 type computers.

The extraction is a partly programmed, partly microprogrammed function - tracking and synthesis are entirely programmed in Assembler ; the memory size occupied by the latter two functions is around 40 kilo bytes of instructions. The elementary or synthetic track data base used by these programs is in the central memory and its size is adaptable to the situation which the system must face.

Concerning performances, we can precise that the extraction of primary plots is regulated in such a way as to supply 15 to 20 % of false plots which, at the level of elementary track initialisation is reduced to no more than 10 % of false tracks. Taking into account the subsequent filtering at the initialisation of the synthetic tracks the percentage of false tracks in the system is very low.

In the same way, the rate of "multiple tracks", that is to say, the cases where a same aircraft results in more than one synthetic track, is practically nil, and is generally due to bad regulation of the radars, or to too numerous detection anomalies.

Finally, on the average, the number of elementary tracks associated with a synthetic track is three, which is sufficient to ensure a good track continuity within the system.

ESTABLISHMENT OF AIR DEFENSE SENSOR REQUIREMENTS FOR AUTOMATIC AIRCRAFT TRACKING

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1. INTRODUCTION AND BACKGROUND

Design and operation of effective air defense systems is becoming increasingly difficult with the proliferation of known as well as postulated threats, both in number and capability. High speed, low altitude aircraft which can either execute a direct attack or employ long range air-to-surface missiles require fast, almost instantaneous, reaction from all elements of the defense system. Moreover, the overwhelming numbers of sophisticated attack aircraft postulated for the near future require that complex weapon management decisions be made quickly and accurately. The requirements for complex decision making and rapid processing of large amounts of data, together with the need to minimize operating costs, especially with respect to personnel, have forced the automation of many of the functions previously performed by human operators.

The two elements of air defense which received the most attention initially were the extremes of the air defense process, i.e., the surveillance sensors and the weapons. As a result, significant technological advances have been made in these areas. More recently, attention has been directed at those functions between the two extremes such as target detection, acquisition, tracking, identification, threat evaluation and weapon allocation. This trend has been a consequence of advances in signal and data processing which allow the digital computer to automatically perform those tasks which historically were assigned to a human operator. Initial attempts at automation were directed toward aiding operators in the decision-making process. More recent automation development place the operator in a parallel monitoring and override mode rather than a serial decision maker. Although this has met with varying degrees of success and acceptance, the trend is obvious.

One significant element of the developments in automation is that the system designer is provided more options because he has more control over both the design and the performance of the decision-making process. As a consequence, the system designer also has more responsibility for effective system operation. Therefore, it is imperative that total system analysis, performance, and cost-effectiveness tradeoffs be accomplished to establish requirements for each of the air defense elements (hardware and software) to assure that the fielded system will counter the proposed threat in the specified environment.

With respect to the design of an automated air defense system, the basic requirement is to develop a matched set of integrated elements which include surveillance (detection, acquisition and tracking), command and control (identification, threat evaluation and weapon assignment), communications, and weapon systems (including the target acquisition and fire control subsystems). For example, even the most sophisticated long range weapon systems may offer little advantage over less sophisticated, shorter range systems if targets cannot be designated (that is, detected, acquired, tracked and processed by the command, control and communication subsystems) at a sufficient range to take advantage of the additional weapon engagement range. Some current missile systems have stand-off ranges of one hundred miles; combined with multiple target acquisition and tracking systems, these missile systems potentially are very effective weapons for air defense. However, current rules of engagement normally require a visual identification of a target before the weapon can be fired. Under the visual rule, where it is difficult to see even large aircraft at more than two miles in good weather (identification can probably occur at no more than half this range), the full capability of the missile system cannot be utilized.

As noted previously, weapon systems and radar technology have received the most attention recently. A real problem in the design of an air defense system is the optimum allocation of requirements to the sensor and sensor processing elements such that current radar technology can be fully utilized to support existing and planned weapons. To this end, this study will consider (Section 2) the functional relationship between air defense requirements and the capabilities of the target acquisition, tracking, identification, threat evaluation and weapon assignment, and weapon subsystems. Some alternative methods for assessing quantitatively the relationship between total air defense system performance and the performance of the individual subsystems are discussed in Section 3; a detailed analytic model of system versus subsystem performance is derived in Section 4. The sensor and sensor processing related functions — that is, acquisition, tracking, identification and acquisition of designed targets by fire control radars — are emphasized in the derivation. Although the communication subsystem is a vital element of an integrated air defense system, communications will not be considered except to note here that a system which can transmit the required information to and from the command and control subsystem without excessive delays due to traffic and queueing problems is required.

2. AIR DEFENSE SYSTEM REQUIREMENTS AND RELATIONSHIP WITH SUBSYSTEM CAPABILITIES

When it is necessary to conduct a defense against a large number of targets with a limited number of weapon resources, it is desirable to use the available weapons in the most effective, efficient manner possible. Optimal weapon utilization requires a command and control function between the surveillance subsystems and the weapons, as shown in Table 2.1. The surveillance functions are contained in steps 1, 2 and 3; the command and control functions are steps 4, 5 and 6; the weapon functions are steps 7 and 8. If some (quantitative) performance requirements for the air defense can be derived or simply specified, then requirements for the subsystems can be derived by considering the event sequence shown in Table 2.1 in the reverse order. In particular, air defense system requirements specify weapon subsystem performance capabilities; weapon subsystem capabilities become the requirements which specify command and control system performance capabilities, which similarly specify surveillance performance capabilities; finally, the weapon, C^2 and surveillance subsystem requirements specify the basic system sensor requirements.

Before any quantitative or even qualitative relationships between AD system performance and the performance of the component subsystems can be derived, it will be necessary to define performance at each level explicitly. The critical step in this task is to define the air defense performance requirements at the system level since these will drive, in turn, each of the subsystem requirements.

TABLE 2.1. EVENT SEQUENCE FOR ENGAGEMENT OF AIR TARGETS

1.	Detection and measurement by surveillance sensors	Surveillance Functions
2.	Acquisition	
3.	Tracking (state estimation)	
4.	Identification	C^2 Functions
5.	Threat evaluation	
6.	Weapon assignment	
7.	Acquisition by fire control system	Weapon Functions
8.	Engagement	

1. AD System Requirements: The basic function of any air defense system, whether strategic or tactical, is to prevent hostile aircraft from accomplishing their assigned missions. Whatever the threat, it is important to minimize the possibility of attacking friendly or even non-hostile aircraft (fratricide). In addition, it is desirable to achieve a cost effective defense; at the least, minimization of weapon utilization is important in order to defend against a sustained attack. Therefore the system level requirements are minimization of: (1) number of threat penetrators, (2) fratricide, and (3) resources expended.

2. Weapon System Requirements: In order to complete successfully the engagement sequence shown in Table 2.1, target designations must occur in time for engagement, preferably at the maximum effective range of the weapon system. This also requires that the weapons be located such that, if used correctly, hostile mission accomplishment can be prevented. Designations should be sufficiently accurate that the intended target can be acquired (with a specified probability) by the fire control subsystem. Also, the performance of an air defense system is adversely effected by false designations (non-existent and non-hostile targets) to the weapon systems. The weapon system requirements may be summarized as (1) site location, (2) designation range, (3) false designation rate, and (4) designation accuracy.

3. Command and Control Subsystem Requirements: The basic function of the command and control subsystem is to coordinate the weapon systems for effective defense in multiple target, limited weapons situations, which implies an optimal (or near optimal) weapon assignment logic. In order to allocate weapons or targets effectively, the subsystem must be able (1) to distinguish hostile from non-hostile targets, (2) to classify threats by function, type, class, etc., and (3) to evaluate the significance of threats with respect to the objectives of the air defense system.

4. Surveillance Subsystem Requirements: The surveillance subsystem provides the basic input to the command and control function. Consequently, the surveillance subsystem must (1) acquire targets at sufficient range that the C^2 and, ultimately, the weapons can operate effectively, and (2) track targets with sufficient accuracy for the identification, weapon assignment and target designation/acquisition functions of the C^2 and fire control subsystems. In addition, false tracks and loss of tracks for valid targets will adversely effect system performance and, therefore, must be minimized.

5. Sensor Subsystem Requirements: The initial elements of air defense are the surveillance sensor subsystems. All subsequent processing, decisions and actions are based on the data provided by these subsystems. In order to assure sufficient quantity and quality of data for the surveillance, command and control, and the weapon subsystems, the sensor performance requirements can be specified by (1) sensor coverage, (2) probability of detection versus range, (3) data rate, (4) measurement accuracies (standard deviations), and (5) false detection rate (and clutter suppression performance).

The discussion above of system and subsystem requirements should be regarded as a summary of some of the basic requirements. For any particular system other more detailed requirements may be appropriate. The discussion should be adequate, however, to illustrate the general method for deriving subsystem requirements from system requirements.

For convenience the system and subsystem requirement parameters have been summarized in Figure 2.1. The most important functional relationships are indicated by the arrows. For example, minimization of mission accomplishment by hostile aircraft implies that the weapon subsystems be located properly and targets are designated to the weapons at ranges which allow the weapons to be used effectively. Again it should be noted that the arrows summarize the most important functional relationships; in a broad sense, each block is a function of everything which follows. For example, minimization of hostile mission accomplishment depends on the false designation rate and the designation accuracy in addition to weapon site location and designation range, all of which depend on the weapon assignment logic, threat classification and evaluation, and identification, etc.

3. SYSTEM ANALYSIS ALTERNATIVES

The primary function of an air defense system, as noted in Section 2, is to prevent attacking hostile aircraft from the accomplishment of their missions. Moreover, air defense should be conducted in such a way that the risk of fratricide (that is, engagement of friendly or non-hostile aircraft with air defense weapon systems) is minimized. Secondarily, the weapon resources expended should be minimized in order to reduce overall defense cost as well as to ensure adequate defense against continued attack.

The dual objective of countering an attack before hostile mission accomplishment while minimizing the expenditure of defense resources suggests a time dynamic situation in which the location of sensors and weapon systems relative to the trajectories and time sequence of the attacking aircraft, the number of attacking aircraft versus the number of weapon systems, the capabilities of the surveillance, command and control, and communication subsystems to process multiple targets and engagements, and so forth, are critical factors. Time varying situations in which geometry, target density and subsystem capacity are important considerations are best analyzed with the aid of time/event simulation models. However, such models are necessarily extremely complex and often expensive to use. Complexity is required in order to evaluate realistically the impact of subsystem design alternatives, particularly in the tracking, sensor netting, and command and control subsystems. In addition to the high cost of the initial development (both for labor and data processing), the data processing costs for valid parametric evaluations of system performance with respect to critical design parameters may be prohibitive. Even when data from the simulation model is obtained, a

great amount of time, effort and care is required of the system analyst to determine the conditions under which the data is valid and to interpret the results with respect to the actual subsystem design.

The alternative to a simulation model is an analytic model. In order to derive an applicable model, it usually is necessary to make a number of simplifying assumptions and to consider only limited situations, such as system performance against a specific threat. However, parametric evaluations are, in general, more easily performed and evaluated with an analytic model than with a simulation model. With care, the results derived from an analytic model for a few specific situations can be used to predict total system performance in a tactical situation. Even when a detailed system simulation exists and can be used cost effectively, it is desirable to develop an analytic model in order to derive preliminary subsystem designs, to bound the application of the simulation model, and to verify and interpret the results of the simulation model.

A simulation model for analyzing air defense systems has been discussed at length by R. Kleinpeter, "Establishing Air Defense Sensor Requirements for Aircraft Tracking and Identification" (NATO Symposium, Brussels; June 1978). Consequently, Section 4 will be devoted to the derivation of an analytic model of the quantitative relationship between system and subsystem performance. Specifically, the model will consist of a set of equations which represent air defense system requirements as functions of the capabilities of the weapon, fire control, weapon assignment, identification, tracking and acquisition functions. The problem of system design often is to obtain performance from the command and control and the surveillance functions which can support given weapon systems. In this context, the design variables in the model are those which specify the performance of the identification, tracking and acquisition subsystems. Once the performance of these subsystems is obtained, actual sensor requirements can be derived by analyses of the individual subsystems. Some procedures for these analyses are discussed by R. Kleinpeter in the paper noted above.

4. AN ANALYTIC MODEL FOR ALLOCATION OF PERFORMANCE REQUIREMENTS

4.1 Model Derivation

In order to derive an analytic model which can be used to evaluate the performance of an air defense system with respect to the tracking, identification and weapon allocation subsystems, the primary measure of performance will be defined to be the probability P_{SE} of engaging successfully a hostile target. Although the probability of successful engagement is not directly related to preventing a hostile aircraft from completing its assigned mission, that mission prevention aspect can be factored into the analysis through weapon and sensor coverage requirements and by the requirement that intercept occur before a specified range. (The latter requirement would be appropriate, for example, for aircraft which launch air-to-surface missiles at a significant range from the intended target; the problem of countering the missile could be considered separately.) The secondary measures of (1) the expected resources expended for an engagement and (2) the probability of fratricide will be discussed after the derivation of P_{SE}.

It will be convenient in the derivation of P_{SE} to consider the probability of engaging successfully specific target types. To this end, let $\{A_1, A_2, \ldots A_n\}$ denote the set of aircraft types (both hostile and non-hostile) to be considered. Whether or not a target of type A_i can be engaged successfully depends on (1) the altitude H_T and the velocity V_T of the target, and (2) a sequence of events within the system which include those shown in Table 4.1. In order to simplify the analysis, it will be assumed that targets are assigned to one of the set of distinct weapon system types $\{W_1, W_2, \ldots W_m\}$ rather than a sequence of weapon systems in which the second system is employed only if the first fails, etc. (The latter situation can be accommodated by a straightforward extension of the derivation below.) In general, the acquisition range, target ID, weapon assignment, designation range and the tracking errors are random variables; the functional relationships which will be assumed for this derivation are shown in Table 4.2.

The probability of engaging successfully target type A_i may be defined for a set of given subsystem responses as follows:

$$P_{SE}(i \mid h_T, v_T; r_A, A_j, W_k, r_D, \sigma_D) = P_{ACQ}(i \mid h_T, v_T; r_D, W_K, \sigma_D)\, P_K(i \mid h_T, v_T; r_D, W_k) \tag{1}$$

where $P_{ACQ}(i \mid h_T, v_T; r_D, W_k, \sigma_D)$ is the probability of acquisition by weapon system W_k of target A_i at range r_D and $P_K(i \mid h_T, v_T; r_D, W_k)$ is the probability of success of W_k against target A_i given that designation occurs at r_D. The probability of success of most weapon systems can be represented by the single trial probabilities $P_{SSK}(r)$ for W_k against A_i as a function of target range:

$$P_K(i \mid r_D, W_k) = \sum_{\beta=1}^{J} \left\{ \prod_{\alpha=0}^{\beta-1} (1 - P_{SSK}(r_\alpha)) \right\} P_{SSK}(r_\beta), \tag{2}$$

where $J = J(r_D, h_r, v_T, W_k)$ is the maximum number of engagement trials given h_T, r_D, v_T and W_k, and where r_β (or r_α) denotes the target range for trial β (or α).

The random variables AR, ID, WA, DR and TE can be eliminated from (1) by integrating with respect to the probability measure induced by the joint probability distribution F(AR, ID, WA, DR, TE):

$$P_{SE}(i \mid h_T, v_T) = \int P_{SE}(i \mid h_T, v_T; r_A, A_j, W_k, r_D, \sigma_D)\, dF(AR, ID, WA, DR, TE). \tag{3}$$

Finally, the probability of engaging successfully A_i can be obtained by integrating (3) against the joint probability density function $p(h_T, v_T)$ of H_T and V_T:

$$P_{SE}(i) = \int_{R^2} P_{SE}(i \mid h_T, v_T)\, p(h_T, v_T)\, dh_T\, dv_T. \tag{4}$$

TABLE 4.1. SUBSYSTEM RESPONSES WHICH DETERMINE SYSTEM RESPONSE

Random Variable	Description	Value Notation
AR	Range at which the target is acquired by the surveillance subsystem	r_A
ID	Target identification from the identification subsystem	j (or A_j)
WA	Weapon assignment from the C^2 function	k (or W_k)
DR	Range at which the target is designated to the weapon system k	r_D
TE	Tracking (prediction) errors: at the time of designation at the time of identification	σ σ_D σ_{ID}

TABLE 4.2. FUNCTIONAL RELATIONSHIPS FOR THE SUBSYSTEM RESPONSE VARIABLES
(R_T = target range)

Random Variable	Functional Dependence
AR	A_i, H_T, V_T
ID	A_i, H_T, R_T, TE
WA	ID, H_T, R_T, V_T
DR	AR, V_T, WA
TE	AR, R_T, V_T

The rather forbidding form of the expression for $P_{SE}(i)$ represented by equations (3) and (4) can be simplified considerably with a few assumptions. Specifically:

1. The tracking errors TE are uniquely determined by the acquisition range, the target range and the velocity of the target.

$$\sigma = H(r_A, r_T, v_T). \tag{5}$$

Also,

$$\sigma \le \sigma_o = H(r_A, r_A - \Delta r, v_{max}), \tag{6}$$

where Δr is chosen to allow a specified number of target updates before identification, weapon assignment and designation; that is,

$$r_D \le r_A - \Delta r. \tag{7}$$

2. Define r_{max} to be the maximum designation range required for a maximum range intercept for all weapon systems $W_1, W_2, \ldots W_m$ against A_i at v_{max}. Assume that weapon assignments are made at r_o, where

$$r_o = \min(r_{max}, r_A - \Delta r), \tag{8}$$

and that designation occurs at the appropriate time for a maximum range intercept for the weapon selected or as soon after weapon assignment as possible. The designation range is then a function of r_A and W_k; in particular,

$$r_D \cdots \begin{cases} \cdots x\,(W_k) \text{ if } r_{max}(W_k) < r_A - \Delta r, \\ \cdots \Delta r \text{ otherwise,} \end{cases} \tag{9}$$

where $r_{max}(W_k)$ is the designation range required for a maximum range intercept of A_i at speed v_T.

3. Assume that identification occurs after a suitable delay from acquisition to obtain a stable track (as noted in assumption 1); the ID is a function of the true identity A_i, target range $r_A - \Delta r$, and the tracking errors σ_{ID}:

$$ID = K(A_i, r_T, \sigma_{ID}). \tag{10}$$

Under these assumptions, P_{SE} can be represented (approximately) as:

$$P_{SE}(i \mid h_T, v_T, r_A) = \sum_{A_j} \sum_{W_k} P_{ACQ}\, P_K\, P_{WA}(W_k \mid A_j, h_T, r_o)\, P_{ID}(A_j \mid A_i, r_T), \tag{11}$$

where P_{ACQ} and P_K are defined by equations (1) and (2), $P_{ID}(A \mid A_j, r_T)$ is the probability of identifying A_i as A_j when the target range is $r_A - \Delta r$, and $P_{WA}(W_k \mid A_j, h_T, r_o)$ is the probability of assigning weapon system W_k given that the ID is A_j.

The dependence of P_{SE} on the acquisition range in equation (11) can be removed by integrating against the probability distribution G of RA:

$$P_{SE}(i \mid h_T, v_T) = \int_R P_{SE}(i \mid h_T, v_T, r_A)\, dG(r_A). \tag{12}$$

If the sensor coverage is such that $P(R_A \geq r_{max} + \Delta) \sim 1.0$, then the only significant dependence on R_A is in the probability of identification. In this case, the expected acquisition could be used (in place of the integral) to obtain adequate results for a first order analysis. For low altitude targets or targets which are not detected until well within the high P_D detection volume, R_A will vary over a range sufficiently small that a single (e.g., expected) value can be used.

The dependence of equations (1), (2), (3), and (11) on target altitude and velocity can be eliminated by defining the target types $\{A_1, A_2, \ldots A_n\}$ to include specific altitudes and velocities. Since targets at maximum velocity will stress the system most severely, a maximum velocity might be used rather than a distribution of velocities; alternatively, an expected or cruise speed could be used. The altitude variable could be handled similarly with low altitude as the stressing situation.

Equations (1) through (4), (11) and (12) represent (to at least a first order approximation) the probability of engaging successfully a specific target type as functions of (1) weapon system performance P_K and P_{ACQ}, (2) the weapon assignment logic through P_{WA}, and (3) the performance of the identification subsystem P_{ID}. In turn, these probabilities are related to range at which the target is acquired and the accuracy to which it can be tracked. The surveillance subsystem (including acquisition and tracking) and the identification subsystem performance measures are directly related to sensor performance measures, particularly measurement accuracies, target resolution, probability of detection, and so forth. Therefore, if the desired air defense performance measures $P_{SE}(i)$ are specified together with the weapon systems $\{W_1, W_2, \ldots W_m\}$, then requirements for identification and surveillance subsystems, and thus sensor requirements, can be determined.

The performance of the weapon, identification, acquisition and tracking subsystems can be estimated adequately with relatively straightforward analytic or simulation analyses. The only real source of difficulty is the performance of the weapon assignment function. If the availability of weapon systems is not considered (e.g., as in the case of system performance against single targets), then weapon assignment can be considered to be a deterministic function of ID and acquisition range, which will simplify equation (11). In general, however, weapon assignment is a time dynamic situation driven by the numbers of weapons and targets, and the time sequence of the targets. An approximation of the time dynamic situation can be derived from (1) the numbers of weapon system type W_k and target type A_j, and (2) a time line analysis of a particular tactical situation of interest. This approach should be adequate for a preliminary derivation of sensor requirements, especially if a time/event simulation model is used to verify the final system design.

Once the individual performance measures $\{P_{SE}(i)\}$ have been derived, a measure of overall system performance against hostile targets can be obtained in several ways; two possibilities are

$$P_{SE} = \max_i \left\{P_{SE}(i)\right\}, \tag{13}$$

or

$$P_{SE} = \sum_i a(i)\, P_{SE}(i), \tag{14}$$

where the maximum (13) or summation (14) is taken over all hostile target types A_i, and where the weighting factors (14) are non-negative. (For example, the actual value of a(i) could be on the priori probability of A_i, if available.) A measure of system performance related to fratricide could be defined as either the probable risk of fratricide or as the probability of actual fratricide. The former would be the probability of identifying a non-hostile aircraft as a hostile aircraft, which could be derived directly from the performance of the ID subsystem. The probability of actual fratricide could be defined analogously to definition (13) or (14) where the maximum or summation is taken over all non-hostile aircraft types A_i.

Finally, a measure of weapon system utilization can be defined as the expected cost of an engagement, whether successful or not, of a target. The expected cost of an engagement of A_i with W_k can be computed analogously to equation (2):

$$E_C(i \mid r_D, W_k) = \sum_{\beta=1}^{J} C(\beta, W_k) \left\{ \prod_{\alpha=0}^{\beta-1} (1 - P_{SSK}(r_\alpha)) \right\} P_{SSK}(r_\beta), \tag{15}$$

where $C(\beta, W_k)$ is the cost of trial β with W_k. The dependence of the cost on the number of trials is included since the cost of the first trial with an interceptor may be different than subsequent trials. (If the number of trials is to be considered rather than actual or relative cost, $C(\beta, W_k = 1)$ for all β, W_k). The expected cost of engaging A_i can be computed from equation (11) by substituting (15) for P_K to yield $E_C(i \mid v_T; r_A)$. The dependence of v_T and r_A can be eliminated by integration as noted in equations (4) and (12). An expected cost per engagement could be defined as in (13) or (14), or a total cost could be defined by

$$E_c = \sum_i n_i E_c(i), \tag{16}$$

where n_i is the number of targets of type A_i and the summation is taken over all aircraft types. If E_c is to represent actual cost (rather than the number of trials attempted), then some additional terms might be added to reflect the cost incurred by engaging successful non-hostile aircraft.

4.2 An Application of the Model to Derive Sensor Requirements

Consider the problem of allocation of performance requirements to the surveillance and identification sensors in order to achieve a specified level of system performance against one specific threat A_j. (For an actual system design exercise, one specific aircraft type may represent the most serious threat relative to the defense objectives or one threat can be identified a priori as the most stressing relative to sensor performance; in either case, system design requirements sensitivity to individual target characteristics is useful.) Moreover, assume that the speed and altitude of the threat are also specified. Finally, assume, for this example, that sufficient weapons are available that weapon assignment becomes a deterministic function of target ID and acquisition range.

With these assumptions, the dependence of the model equations on i, h_T, and v_T can be eliminated; thus equation (11) becomes

$$P_{SE}(r_A) = \sum_{A_j} P_{ACQ} P_K P_{ID}(A_j | A_i, r_A), \tag{17}$$

where

$$P_K = P_K(r_D, W_k), P_{ACQ}(r_D, W_k, \sigma_D). \tag{18}$$

Note that $W_k = W_k(r_A, A_j)$ in equation (18); also $r_D = r_D(r_A, W_k)$ and $\sigma_D = \sigma_D(r_A, r_D)$ by assumptions 1 and 2 of Section 4.1. The measure of system performance P_{SE} is given by

$$P_{SE} = \int_R P_{SE}(r_A)\, p(r_A)\, dr_A, \tag{19}$$

where $dF(AR) = P(r_A)\, dr_A$ (equation 3). For given weapons, equations (17), (18) and (19) completely specify system performance as a function of the probability distribution of the acquisition range AR, the probability distribution of the identification decision and the function which specifies the tracking errors. Each of these functions can be developed as functions of sensor performance parameters such as detection range, measurement accuracy probability of false alarms, and so forth. (It is assumed that the functions P_K and P_{ACQ} are specified for the weapon subsystems under consideration.)

Tracking accuracies can be developed analytically as a function of the tracking algorithm and sensor measurement accuracy. For example, the data in Figure 4.1 was derived in order to compare the tracking performance of two specific radars· the actual measurement accuracies are shown on the figure. (In this particular case, the only difference between the two radars is the signal processor, and, in particular the clutter rejection capability of the processor.) In order to generate the data, it was assumed that some form of an automatic report-to-track correlation logic would be used to process the radar reports. For the actual tracking (that is, estimation process) it was assumed that a Kalman filter would be used for two independent cartesian coordinates (X, Y). A constant velocity model was assumed for the state equation (or prediction equation) in which a zero-mean error term with a standard deviation equivalent to a 0.5 g maneuver was included. The variance of the independent (X, Y) measurements was estimated from

$$\sigma^2 = \sigma_R^2 + (R\sigma_\theta)^2, \tag{20}$$

where R is the target range, and σ_R and σ_θ are the standard deviations of range and azimuth measurements, respectively. Thus the data shown above represents the worst case geometry for the conversion from polar to cartesian coordinates. The measurement variance equation (20) could be modified for targets on a specific azimuth if desired.

The data shown in Figure 4.1 was developed from a theoretical covariance analysis. It was assumed implicitly that the target was detected and that the target report was correctly correlated with the track on every scan. Situations in which the probabilities of detection and correct report-to-track correlation are less than unity can be analyzed with Monte Carlo simulation methods.

The performance of various aircraft identification systems has been analyzed at Hughes Aircraft Company. The performance of an example system is shown in Figure 4.2; the ID system is based on measurements of aircraft speed and altitude, engine characteristics and radio frequency characteristics of emitters on the aircraft together with flight plan correlation and IFF response data. The figure represents the probability of correctly identifying one of twenty military aircraft. The abscissa of the graph does not represent time to any scale but only represents the chronological order in which data becomes available. The dashed lines represent the performance relative to hostile/nonhostile identification; the solid lines represent performance relative to identification by aircraft class.

The probabilities of correct identification shown on the graph were derived from the individual probabilities $P_{CLASS}(A_j | A_i, r)$ where the range r at the time of ID is assumed to be 100 nmi from the surveillance radar used for flight plan correlation and IFF. The probabilities are based on the assumption that the EC and ESM data are correctly correlated with the radar track; the probability of correct data correlation is a function of the track accuracy at each

sensor and the system registration and alignment errors. The values of P_{ID} to be used in equation (17) are specified by

$$P_{ID}(A_j | A_i, r_A) = P_{CDC}(r_{ID}) P_{CLASS}(A_j \; A_i, r_{ID}), \tag{21}$$

where r_{ID} is the target range at which the system ID is obtained and where P_{CDC} is the probability of correct data correlation at r_{ID}.

Lastly, consider the acquisition range distribution. The range at which any particular target is acquired as a system track is a function of the radar design, including the detection range, probability of false alarm, and signal processing.

The promotion logic component of acquisition, generally specified as requiring m detections in n scans (m/n), is used as the basis of establishing that the resulting system (firm) track has a high confidence of being valid. Typical criteria for acquisition with a single sensor are: 2/2, 2/3, 3/3, 3/4. The two-hit logics (2/2 and 2/3) generally provide a shorter acquisition than the three-hit logics but a considerably higher false acquisition rate. Among the three-hit logics, the 3/3 logic provides significantly longer acquisition time than the 3/4 logic, unless the detection probability is close to unity in the region where the targets first appear, since it allows for no misses in three consecutive scans. However, the logics which allow misses (e.g., 3/4) have higher false acquisition rates than those not allowing misses (e.g., 3/3). The false acquisition rate will depend largely on how effectively the radars can suppress clutter.

Comparison of some promotion logics is presented in Figure 4.3. The abscissa is the theoretical, single look 0.9 P_D range of the radar and the ordinate is the cumulative 0.95 probability of acquisition range, both normalized to the maximum instrumented range. Note that depending on the promotion logic and 0.9 P_D range relative to the instrumented range the acquisition range varies significantly. For an air defense system it is the acquisition range that is most important for total system performance and this is the parameter that should be specified by the system designer. For automated systems, unless the P_D range of the sensor is derived through system performance measures, such as acquisition range, with consideration of promotion logic, it may be either unnecessarily constraining to the sensor designer or result in poor system performance.

Now that the relationships between the sensor design parameters and the performance parameters of the individual subsystems have been established, sensor performance requirements can be derived from equations (17), (18) and (19). In order to illustrate this process, assume that a desired value of P_{SE} is specified. One method for obtaining sensor requirements is outlined in the sequence of steps below.

1. From equation (19),

$$P_{SE} \geq P_{SE}(r_A') \, P(AR > r_A') \tag{22}$$

   which establishes desired values for $P_{SE}(r_A')$ and $P(AR > r_A')$.

2. The required value of $P_{SE}(r_A')$ (from step 1) can be used to establish requirements for P_{ACQ}, P_K and P_{ID} through equation (17).

3. The requirements for P_K and P_{ACQ} imply requirements for the designation range r_D and the track accuracy σ_D through equations (18).

4. The required designation range and the requirement for P_{ID} specify the range at which the identification process illustrated in Figure 4.2 must be completed, which, in turn, will specify the performance of any special sensors which may be required to obtain the required value of P_{ID}. In addition, if special sensors are required, the data correlation requirements may impose further requirements on track accuracy.

5. Curves such as those shown in Figure 4.1 can be used to specify data rate, track time and measure accuracy requirements.

6. Finally, the designation rate and track time requirements specify the acquisition range requirement r_A' which, together with $P(AR > r_A')$, specify the detection range and the promotion logic illustrated in Figure 4.3.

The sensor measurement accuracy, data rate and detection range requirements constitute the fundamental sensor design requirements. These requirements, together with false alarm and clutter suppression requirements (which could be derived from a similar analysis of specified requirements for false weapon system designations) can be used to derive the sensor hardware and signal processing design.

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83496-2

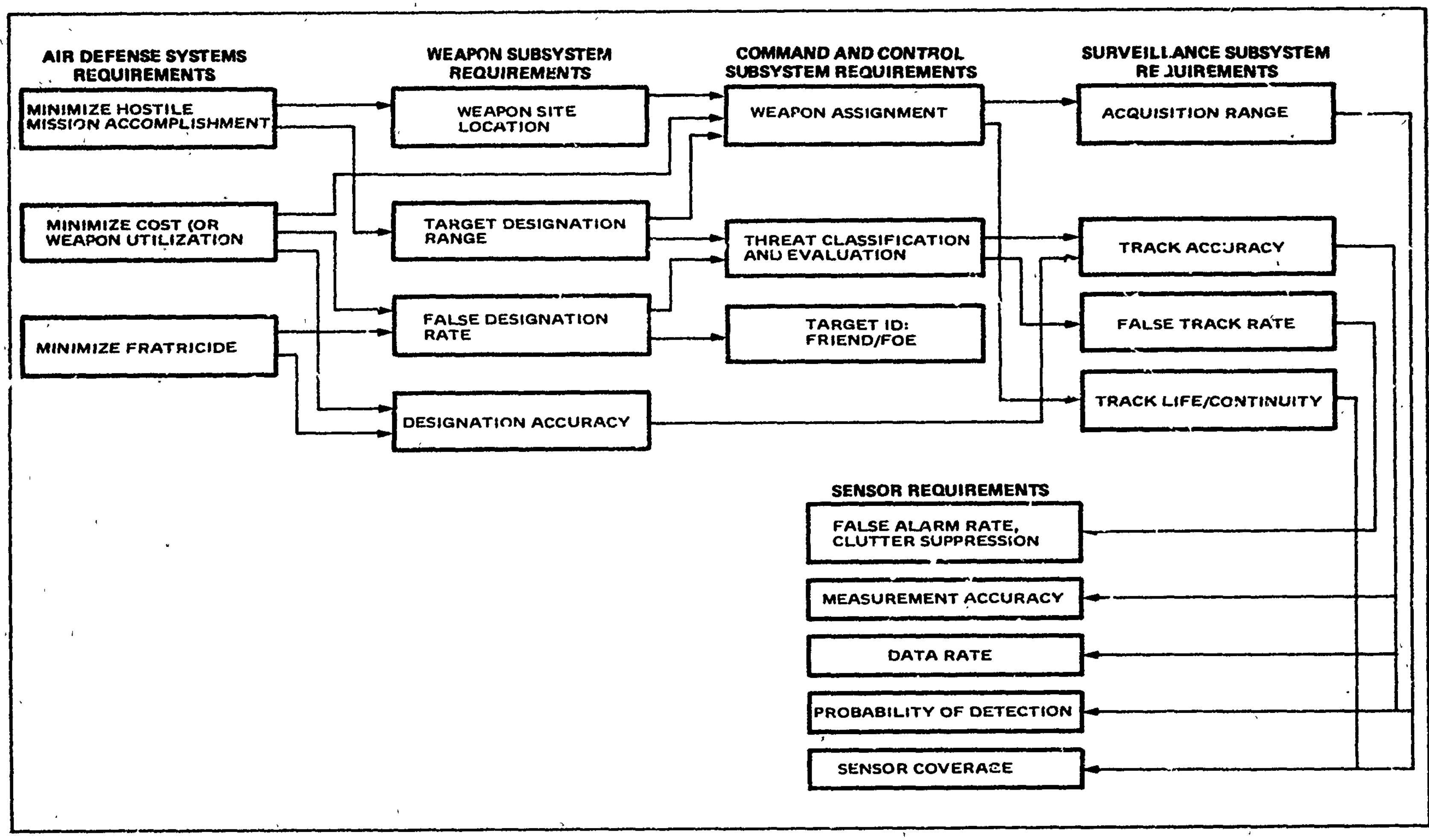
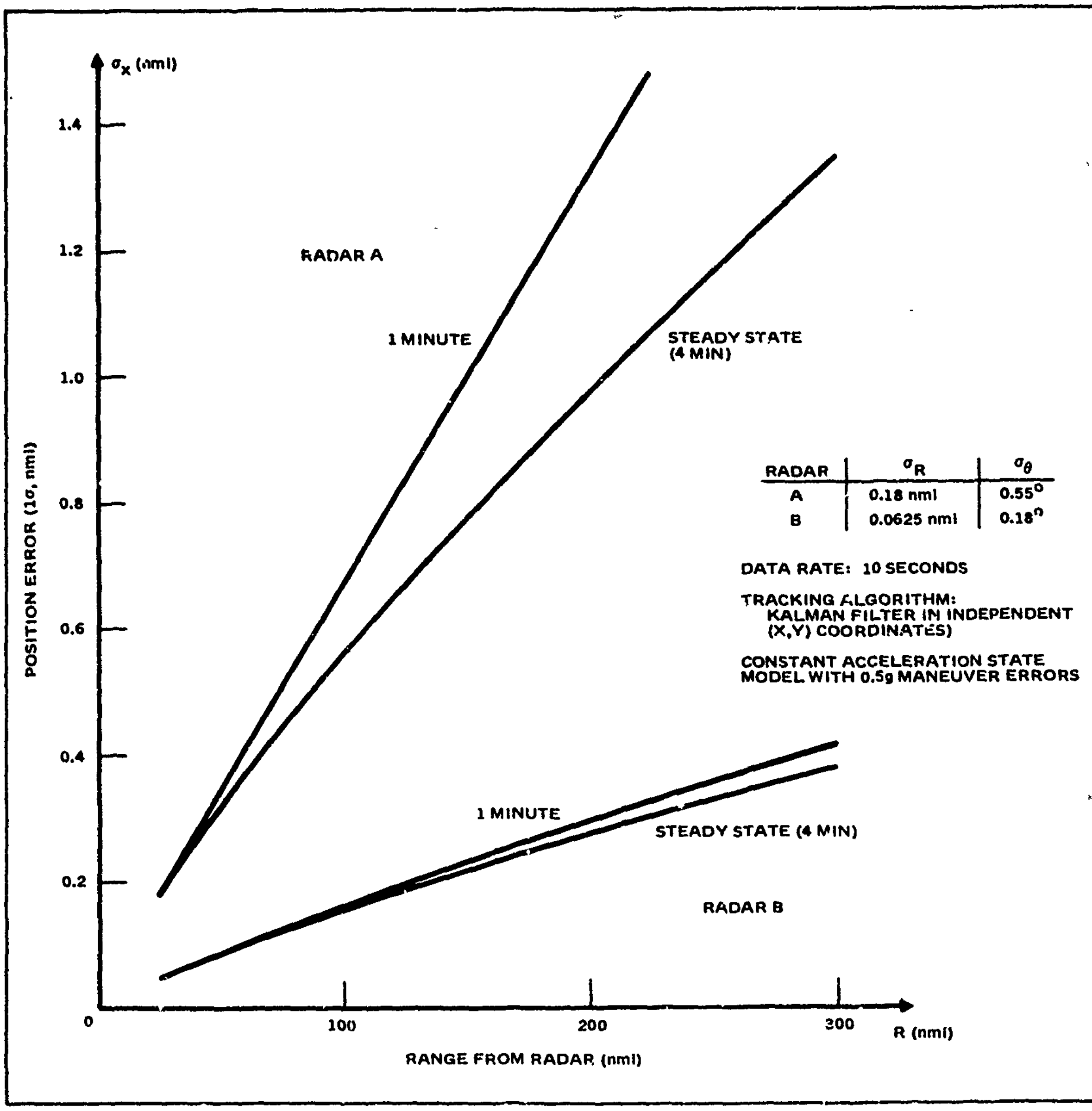


Fig.2-1 Some important functional relationships between system and subsystem performance



RADAR	σ_R	σ_θ
A	0.18 nml	0.55°
B	0.0625 nml	0.18°

Fig.4-1 Track accuracy versus target range

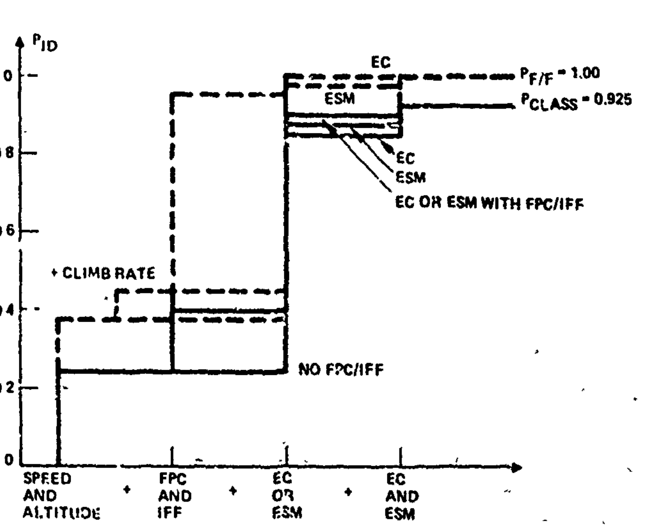


Fig.4-2 Probability of correct identification of one of 20 aircraft

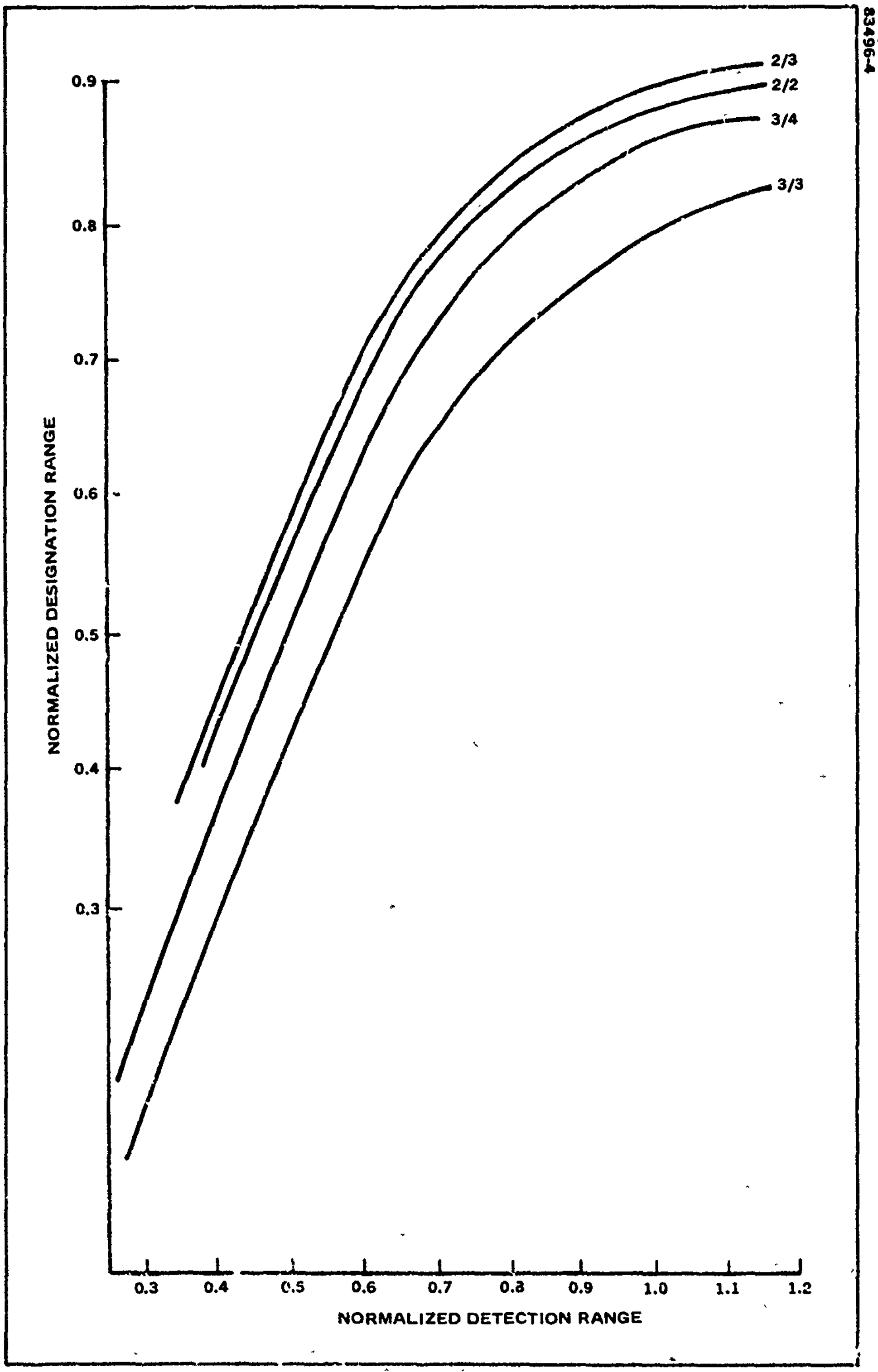


Fig.4-3 Radar performance reference range

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